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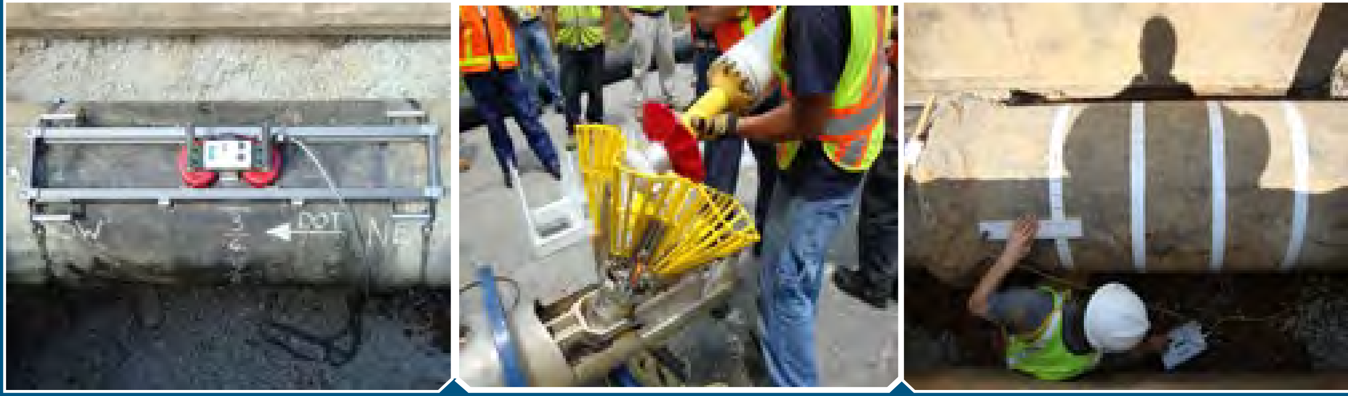
# Field Demonstration of Innovative Condition Assessment Technologies for Water Mains: Acoustic Pipe Wall Assessment, Internal Inspection, and External Inspection

## Volume 1: Technical Report
## Volume 2: Appendices



Office of Research and Development

# FINAL REPORT

# FIELD DEMONSTRATION OF INNOVATIVE CONDITION ASSESSMENT TECHNOLOGIES FOR WATER MAINS: ACOUSTIC PIPE WALL ASSESSMENT, INTERNAL INSPECTION, AND EXTERNAL INSPECTION

## VOLUME 1: TECHNICAL REPORT

by

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# ABSTRACT

Nine pipe wall integrity assessment technologies were demonstrated on a 76-year-old, 2,057-ft-long portion of a cement-lined, 24-in. cast iron water main in Louisville, KY. This activity was part of a series of field demonstrations of innovative leak detection/location and condition assessment technologies sponsored by the U.S. Environmental Protection Agency (EPA). The main goal of the demonstrations was to acquire a snapshot of the current performance capability and cost of these innovative technologies under real-world pipeline conditions so that technology developers, technology vendors, research support organizations, and the user community can make more informed decisions about the strengths, weaknesses, and need for further advancement of these technologies.

Pipe wall integrity assessment was one part of a comprehensive water pipeline condition assessment demonstration where six inspection companies operated 12 technologies (nine for pipe wall integrity assessment and three for leak detection) that were at various stages of development and provided different types and levels of leak and/or structural condition data. Technologies were included for wall-thickness screening (i.e., average wall loss over many tens of feet), for video screening of internal pipe condition, for detailed mapping of wall thickness, and for leak detection. Both in-line and external inspection technologies were demonstrated. The inspection technologies used visual, mechanical, acoustic, ultrasonic, and electromagnetic methods for acquiring leak and pipe condition data.

This report presents the results of the following nine pipe wall integrity assessment technologies:

Three technologies for average wall thickness screening are discussed including Sahara® Wall Thickness Testing (WTT), SmartBall™Pipe Wall Assessment (PWA), and ThicknessFinder. These inspection technologies acquire pipe condition data in the form of general pipeline condition or average wall loss over a specified interval.

Three technologies are discussed that use inline inspection of the entire pipeline length including Sahara Video®, PipeDiver® remote field eddy current (RFEC), and See Snake® RFT. These inspection technologies can acquire pipe condition data, such as metal loss, size of defects, and/or cracks.

Three technologies are discussed that use external inspection at selected excavation points including External Condition Assessment Tool (ECAT), Hand Scanning Kit (HSK) and Crown Assessment Probe (CAP). These inspection technologies can acquire pipe condition data within an excavation and use models to predict the condition of portions of the pipeline that remain buried.

Upon completion of the field demonstration effort, the 24-in. diameter test pipe was removed by Louisville Water Company (LWC) to prepare for installation of a 30-in. diameter replacement line. As the 24-in. line was being removed, the EPA's contractor selected 12 pipe lengths for post-demonstration confirmation of the reported condition assessment technology results. Pipe segments were selected using the inspection results reported by each technology vendor and visual assessment of the pipe condition as it was removed. The pipes were grit blasted to remove coating, corrosion and graphitization and the amount of metal loss was quantified manually and with a laser scanner. For each technology, inspection results were compared to the dimensions and locations of machined defects and/or of naturally-occurring defects found after excavation to evaluate the performance of the pipe wall integrity assessment technologies. Each company provided a written report on the condition of the test pipe, with some reporting anomalous pipe segments and others reporting the size, depth, and location of specific defects along the test pipe. This report covers acoustic pipe wall assessment, internal inspection, and external inspection. Volume II includes assessment data for excavated pipe and vendor reports. A companion report (Nestleroth et al., 2012) provides information on the leak detection and location portion of the technology demonstration. The field demonstration phase was conducted in 2009. The post-demonstration ex situ pipe characterization, and report preparation and review was conducted in 2010, 2011, 2012, and 2013.

# ACKNOWLEDGMENTS

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Echologics Engineering Inc.
The Pressure Pipe Inspection Company
Pure Technologies, Ltd.
Russell NDE Systems Inc.
Advanced Engineering Solutions Limited
Rock Solid Group Pty. Ltd.

# EXECUTIVE SUMMARY

The state of the art in condition assessment technologies for water mains is still developing and water utilities are interested in third-party, independent sources of information on the capabilities of innovative inspection technologies. Technology demonstrations with a range of real-life defects and conditions are particularly valuable to water utilities and can play a vital role in accelerating the adoption of appropriate, innovative condition assessment technologies. A field demonstration program was conducted to evaluate condition assessment technologies applicable to the inspection of cast iron water mains. It is critical that utilities have the capability to undertake reliable condition assessment of cast iron pipelines in order to prevent failures and/or premature rehabilitation or replacement.

The main goal of the demonstration program was to acquire a snapshot of the performance capability and cost of applicable inspection technologies under real-world pipeline conditions so that technology developers, technology vendors, research organizations, and the user community can make more informed decisions about the strengths, weaknesses, and need for further advancement of these technologies. As part of this research effort, several emerging and innovative inspection technologies were demonstrated on a 76-year-old, 2,057-ft-long portion of a cement-lined, 24-in. cast iron water main in Louisville, KY. This report presents the results from the acoustic pipe wall assessment, the internal inspection, and the external inspection technology demonstrations. A companion report (Nestleroth, B. et al., 2012) discusses the results of the leak detection technologies. The field demonstration phase was conducted in 2009. The post-demonstration ex situ pipe characterization, report preparation, and review was conducted in 2010, 2011, 2012, and 2013.

This report presents the results of a total of nine pipe wall integrity assessment technologies including:

Average wall thickness screening with Pressure Pipe Inspection Company's (PPIC) Sahara® Wall Thickness Testing (WTT), Pure's SmartBall™ Pipe Wall Assessment (PWA), and Echologics' ThicknessFinderRT. The methods used sensors and data recording equipment from their leak detection platforms, along with a method to introduce sound energy into the pipeline.

In-line inspection of the entire pipeline length with two remote field eddy current (RFEC) methods called PPIC PipeDiver® RFEC and Russell NDE Systems Inc. See Snake® Remote Field Technology (RFT), and a video system called Sahara Video®.

External inspection at selected excavation points using Advanced Engineering Solutions, Ltd. (AESL) External Condition Assessment Tool (ECAT), Rock Solid Group's (RSG) Hand Scanning Kit (HSK), and RSG's Crown Assessment Probe (CAP).

All of the technologies are commercially available and most have been reported to have been improved since the demonstration was conducted in 2009. Many of the companies have recently been acquired or merged. PPIC is now part of Pure. Echologics is a subsidiary of Mueller Water Products. Rock Solid Group has successfully licensed their technology globally including a number of U.S.-based licensees that offer broadband electromagnetic (BEM) inspections locally. The See Snake® demonstrated by Russell NDE Systems Inc. is now provided by a subsidiary, Pipeline Inspection and Condition Analysis (PICA). AESL technology was developed and operated in the United Kingdom and has been leased for operation in Europe and Australasia for several years, and more recently in North America.

These nine technologies were demonstrated to evaluate their capabilities to assess the structural condition of a straight, cement-lined, 24-in. cast iron water main with bell and spigot joints that are sealed with leadite. The test pipe had a burial depth between 3.5 and 6.0 ft and wall thicknesses ranging from 0.68 to 0.78-in., as measured periodically during routine maintenance activities. The test pipe historically operated at pressures between 45 and 50 pounds per square inch (psi), while transmitting 4 to 6 million gallons per day (MGD) of flow. Under the Louisville Water Company's (LWC) Main Replacement and

Rehabilitation Program, a portion of 24-in. diameter cast iron transmission water main along Westport Road was scheduled for replacement. LWC agreed to make this portion of the pipe available for field demonstration, as well as provide necessary on-site assistance. Immediately after the field demonstration was completed, the 24-in. water main was replaced with a 30-in. line in the same location. This allowed for the opportunity to exhume portions of the pipeline in individual 12-ft lengths for further assessment.

Many logistical, operational, and performance aspects of these nine technologies were observed over the course of the demonstration. The logistical and operational requirements affect the feasibility and complexity of use for the various inspection tools. Several steps, which varied depending on the technology function, were involved in demonstrating technology performance. The vendors provided their assessment of the test pipe condition, with some reporting average or effective wall thickness for various spans of pipe; others reporting anomalous pipe segments; and still others reporting the size, depth, and location of specific defects along the test pipe. Pipe segments were then selected for detailed ex situ evaluation based upon the vendor inspection results, and visual assessment of the pipe condition as it was removed from the ground by the utility. The technology inspection results were compared to the dimensions and locations of machined defects and/or naturally-occurring defects to evaluate the performance of the pipe wall integrity assessment technologies. The amount of metal loss from 12 exhumed pipes was quantified manually and/or with a laser scanner and compared, where applicable, to the vendors' in situ inspection results. In addition, cost estimates to implement the various technologies for the inspection of a 24-in. cast iron pipe were also requested and are documented in this report, along with estimated site preparation costs for those activities typically conducted by the utility.

With respect to pipe deterioration measuring capabilities of the innovative technologies, the main focus was on the capability of the devices to measure metal loss, primarily due to pitting, graphitization, general corrosion, and machined defects. An exception is Sahara Video, which provided visual data only on the location and condition of the cement mortar liner defects, valves, and connections.

The pipe wall integrity inspection demonstrations did not evaluate technology capability for all types of failure modes. For example:

- Interior metal loss was not evaluated. The pipe had a cement mortar liner, which appeared to be in good condition based on CCTV and visual observation of excavated pipes. It was assumed that a sound cement liner indicated little or no corrosion in the adjacent pipe wall. Removing the cement mortar liner to assess the inner pipe wall was not within the project scope.

- Cracks were not a priority, and were not generally present. Significant cracking was not observed in the 12 excavated pipes that were characterized in detail, nor were cracks included in the set of machined defects, nor did the technologies with crack-detection capability report cracks. The leak detection demonstration previously conducted indicated few through-wall cracks.

- Detection of mis-aligned joints was not a capability of the demonstrated technologies, nor was mis-alignment found during documentation of the pipe characteristics.

Machined Defects

A milling machine on a magnetic base was used to create 18 machined metal loss defects that were installed in Pits 2, 4, 5, and F. The manufactured defect sizes ranged from approximately 1- to 6-in. in length with depths varying between 20% up to 70% wall loss. The intent of installing machined corrosion defects was: (a) to provide three defects for vendors to calibrate their inspection devices, and (b) to create a set of 15 "hidden" defects whose characteristics were only known by the EPA contractor, not the inspection vendor. In this way, the demonstration could help to define both the current capability and future challenges for each of the inspection technologies. For technologies that report the average wall thickness over tens or hundreds of feet, detection of the machined defects in this demonstration is not a relevant parameter, since the machined defects cause only a minuscule change in average wall thickness for even a single length of pipe.

Condition Assessment of Exhumed Pipes

A post-demonstration confirmation study was conducted in order to select, characterize, and compare the condition of exhumed pipe samples to the pipe inspection data that was collected by the inspection technology vendors during the field demonstration in Louisville, KY. The confirmation study included an assessment of the original wall thickness, inside cement coating thickness, and pipe outer diameter (OD) and wall loss measurements for 12 exhumed pipes. Prior to measuring external wall loss, the pipes were sandblasted to a NACE-2 Near-White Blast Cleaning to expose degradation. While this method will remove a small amount of good cast material, a less aggressive NACE-3 preparation did not remove all of the graphitization in the deepest pits. Therefore, measured metal loss may be slightly greater than actual condition. The exhumed pipes were assessed manually and/or with a laser scanner in order to determine the extent of metal loss. The extent of metal loss was characterized by total volume loss, number of pits (with loss greater than 50% of depth), maximum pit depth, and largest corrosion patch dimensions. This report presents the rationale for selection of the 12 exhumed pipe segments and the methodologies used for the pipe condition assessment during the post-demonstration confirmation study.

The wall thickness was measured at undeteriorated locations around the circumference at the spigot, center and bell; the inside cement coating thickness was measured at the spigot; and the circumference was measured at three undeteriorated locations. In general, the pipe wall thickness at the spigot was the same around the circumference, confirming that the pipe is spun cast iron. For the 12 exhumed pipe samples, the average wall thickness of the undeteriorated portions of the exhumed pipes was 0.786-in., the standard deviation was about 3%, and the pipes tended to be slightly thicker at the bell than at the spigot. The average outside diameter of the 12 pipes was 25.82 inches with a standard deviation of 0.03 inches. Thus, the average inside diameter of the pipe was 24.25-in. The cement liner had an average thickness of 0.25-in, but it was thicker at the top (average 0.33 inches) than at the bottom (average 0.14 inches) with a standard deviation of 0.06-in..

For the areas of the 12 exhumed pipes with corrosion and graphitization, the remaining metal was calculated by subtracting the anomaly depth from the local wall thickness. The depth of the pits was measured by two methods. For the eight pipes with the least corrosion, corrosion was mapped in a ½ x ½ in. grid using a micrometer and bridging bar. For the four pipes selected for verification judged to be in the worst condition, a laser-based coordinate-measuring machine (CMM) was used for automated measurement of the metal loss. This method uses laser beams that are projected against the surface of the pipe. Many thousands of points in a 0.040 x 0.080 in. grid are then taken and used to determine the size and position of corrosion by creating a three-dimensional (3D) image of the pipe. An area on one pipe was assessed with both methods to ensure comparable results were attained.

While each of the 12 pipes had some amount of metal loss, the pipe condition was generally good. The greatest average wall loss was calculated for all of the pipes and was less than three percent. The number of pits greater than 50% deep was also counted; one pipe had 13 pits, four pipes had four to six pits, four pipes had one or two pits, and three pipes had none greater than 50% deep. The deepest pit was 85 percent through the wall. Also, the cement mortar liner appeared in generally good condition. Based on the above information, EPA’s contractor considered the exhumed pipes to have minimal deterioration. While none of the pipes appeared to have significant degradation, the pipes were assigned a relative condition assessment score based upon volume loss and number of deep pits as described in the report.

## Condition Assessment with Non-Destructive Technologies

As noted above, many aspects of the wall thickness assessment technologies were observed and documented over the course of the demonstrations. This section provides an overview of the demonstration results and their significance.

Ten logistical and operational requirements are documented for each demonstrated technology. The requirements addressed are: equipment logistics, utility preparation, number of technicians needed, pipe access or contact points, sterilization of components that contact water, real-time data, condition assessment, on-site report, and operator intervention. This information provides insight into the ability of the tools to mobilize, access the pipe, and operate under various field conditions for a 24-in. cast iron pipe. This information will help utilities to gauge the logistical and operational feasibility of using these technologies at their sites.

Most of the technologies were in the early stages of commercial deployment. For some of the technologies, this demonstration was the initial or early use of the inspection tool or procedure. The inspection technologies are not strictly comparable since, for example, they are designed to meet various water pipeline operators' needs with respect to inspection goals, levels of intrusion, complexity of operation, resolution of results, and implementation approaches. The lowest resolution system provided average wall thickness measurements at intervals of a few hundred feet; this system required one person with two suitcases about a half a day to perform the task and required seven excavations to the top of the pipe. The highest resolution system measured the location as well as depth, length, and width of individual metal loss anomalies along the pipe length and circumference. This was also an intrusive technology, since it was an internal inspection system that was nearly full circumference and for this use the pipe had to be drained, eight ft of pipe had to be removed at each end, and a dedicated winch truck employed.

For the average wall thickness screening assessments (that used sensors and data recording components from leak detection platforms, along with a method to introduce sound energy into the pipeline), the following observations were found.

- ThicknessFinder worked from the outside of the pipe at excavations and had the coarsest resolution. It provided average wall thickness readings for seven segments of pipe that averaged 293 ft in length. Numerical values of average effective wall thickness were provided, along with a qualitative description of the pipe condition. The results of the inspection classified the pipes as in good condition, but estimated the average effective wall thickness loss at 14% to 20%, reflecting more severe deterioration than the exhumed pipes, which were found to have <2.6% wall loss. The capability of the technology to identify large areas of significant corrosion could not be evaluated, since the test pipe was in overall good condition, i.e., < 2.6% wall loss in the 12 pipe lengths characterized in detail. The inspection tool was able to be successfully deployed under site conditions. ThicknessFinder was operated in the demonstration with the pipe full, but not flowing, and hence not producing a noisy discharge to the sewer. One person and two suitcases of equipment required about a half a day to perform the task. Eight excavations were needed. The water was not contacted. Longer distances would require more excavation points. This technology was in an emerging technology status at the time of the demonstration.
- Sahara® WTT provided measurements over 33 ft intervals using a sensor in the pipe and excitation at excavations. The inspection results were reported as an average wall thickness loss ratio. The inspection tool was successfully deployed under site conditions. The inspection report indicated that a wide range of conditions were present in the pipe with degradation, in terms of wall thickness loss, exceeding 30% for three intervals. However, in the assessment of 12 exhumed pipes, only minimal wall loss was observed. Sahara® WTT provided data for about 1040-ft out of the 2057-ft test pipe due to reasons such as the close proximity of the internal and external sensors, presence of large air pockets, or noise from the pipeline discharge, which masked acoustic activity. Flow in the test pipe was necessary to transport the tethered sensor through the pipe. For this demonstration the flow had to be discharged to the sewer, which likely

would be unnecessary for an in-service line or could be done sufficiently far from the tested pipe to prevent interference. A dedicated winch truck with two operators was needed; the inspection was completed in a day. One excavation point and installation of a 2-in. fitting were required; a second excavation point and fitting would be needed if length increased significantly. A sterilized sensor and tether was inserted in the pipe; disinfection efficacy assessment was not within the project scope for any internal technologies. This was a very early use of this emerging technology and tool performance could be improved with further calibration to pipe excavation and characterization information from the field. For example, a utility could perform a few excavations in areas of suspected wall loss to confirm the condition of the pipe and subsequently work with the vendor to improve the calibration and post-analysis of the Sahara® WTT results with excavation information from their site. This confirmation of inspection results is a common practice in other industries (e.g., oil and gas pipeline inspections) where typically up to five locations are dug to confirm and better calibrate inspection results.

- SmartBall™ Pipe Wall Assessment made acoustic velocity measurements approximately every 2 ft using a sensor inserted in the pipe and a sound source at the ends and middle of the main. The measurements were analyzed and twelve spans of pipe, from 14 to 102 ft in length were identified as having acoustic anomalies with the designation of regions noted to have reduced stiffness. Four of the exhumed pipes fell within regions designated as having "reduced stiffness" and three fell within regions designated as "normal" via SmartBall™ inspection; the worst of the exhumed pipes were in spans identified as having reduced stiffness. Two operators were needed with equipment delivered by overnight package delivery. Two excavation points (each end) were required with a 4-in. fitting installed; greater distances than those demonstrated can be done with one insertion. A sterilized sensor and catching equipment were inserted in the pipe. SmartBall™ PWA provided data for about 1050-ft out of the 2057-ft test pipe. It had difficulties assessing the second half of the test pipe potentially due to SmartBall™ PWA being unable to detect the acoustic signal from the third pulser, which was nearest the large amount of noise produced by discharge of water from the test pipe, which would likely be unnecessary or avoidable in an in-service line. This was a very early use of this emerging technology and tool performance could be improved with further calibration to excavation information from the field. For example, a utility could perform a few excavations in areas of suspected wall loss to confirm the condition of the pipe and subsequently work with the vendor to improve the calibration and post-analysis of the SmartBall™ results with excavation information from their site. This confirmation of inspection results is a common practice in other industries.

For the in-line inspection of the entire pipeline length with two remote field eddy current (RFEC) methods, and one video method, the following observations were found.

- PipeDiver® RFEC made measurements in fine intervals along the full length of the pipeline; signal analysis yielded prediction of anomalous or good condition for each of the 12-ft pipe lengths, including those that were subsequently exhumed and characterized in detail. It successfully identified pipes independently determined to be in good condition. PipeDiver® results were mixed compared to the EPA contractor's assessment when attempting to discriminate between levels of degradation in pipe that was in overall good condition (i.e., < 4% overall wall loss). In those pipes, some substantial corrosion patches, deep corrosion pits, and up to 6 pits > 50% did not cause pipes to be reported as anomalous. This may or may not be a concern, depending on inspection goals and criteria. PipeDiver® results indicated more anomalies in the second half of the test pipe, whereas See Snake® indicated significantly more, and more severe, metal loss anomalies in the first half of the pipe (Figure 2-2). The bell and spigot joint made a clear pattern in the raw data; one method used to identify anomalous pipe was observing disruptions in this pattern. The inspection tool was able to be successfully deployed under site conditions, although the initial launching process was modified due to pipeline obstructions (e.g., gaps in a downstream joint). Two excavation points (each end) were required with a 12-in. fitting installed; greater distances than those demonstrated can be done with one deployment. Complex equipment was used to launch and receive the sterilized inspection tool. The tool was half the diameter of the pipe. This was the first use of this technology for wall thickness assessment in a cast iron main and tool performance could be improved with further calibration to pipe condition information from field excavations. Additional sensors may enable more detailed resolution of pipe defects.

- See Snake® RFT provided the axial and circumferential location of individual metal loss anomalies as well as the dimensions (depth, length and width). While each reported defect does not map directly to each actual defect, of the 12 pipes that underwent detailed examinations, the pipe lengths with the largest number of metal loss indications were also reported by See Snake® to have a large number of pits. Additionally, the pipe lengths that showed minimal degradation in the detailed examinations were also correctly identified by See Snake® as having few or small anomalies. As noted above, See Snake® indicated significantly more, and more severe, metal loss anomalies in the first half of the pipe, whereas PipeDiver® reported more anomalies in the second half of the pipe (Figure 2-2). The bell and spigot joints could be seen in the raw data, but not characterized in detail. Eight joints were identified as anomalous. See Snake® was not able to characterize any of the machined calibration or test defects, and the vendor identified the potential cause for the problem as magnetic permeability noise. The vendor identified four potential causes of the interference arising from either the installation process for the artificial defects or the previous operation of other electromagnetic inspection devices in the vicinity. The inspection tool was able to be successfully deployed under site conditions. The implementation was intrusive for the demonstration as the pipe had to be dewatered, cut, and a pull cable had to be threaded for this inspection. Ultimately, the See Snake® is designed to be launched in a live pipeline; however this was not possible for the demonstration because it was a prototype system. Two excavation points (each end) were required with the pipe cut to launch and receive the tool. The pipe had to be drained and water swabbed out. The tool was somewhat less than the inside diameter of the pipe. This was the first use of this version of the technology for a 24-in. cast iron water main.
- Sahara Video® is used to detect corrosion on the inside pipe surface. The camera provided an image of a portion of the inside of the pipe. Sahara Video® provided results that confirmed that the pipe lining was in generally good condition and had minimal degradation or delamination. Air pockets, ranging from small to large in size, were also discovered during the video inspection, but could not be further verified as the air pockets dissipated with flow. Operations are similar to the Sahara® WTT tool. The results of the video were not independently verified, although the inner lining was found to be in good condition based upon visual examination of the excavated pipe.

Technologies for external inspection at selected excavation points are usually significantly simpler to implement than in-line inspection devices. The demonstration showed the following differences among the external inspection technologies in implementation approach and potential results.

- The AESL ECAT device provided axial and circumferential location of individual metal loss anomalies, as well as the dimensions (depth, length and width) for defects at specific excavation locations. In addition to the pipe condition data from the ECAT magnetic flux inspection tool, AESL collected ultrasonic wall thickness measurements, and coating assessments and soil data (i.e., soil resistivity, redox, pipe-to-soil potential, and pH;) from the three pits. They also collected the soil data from seven other pits along the test pipe. AESL also used an extensive analysis procedure to derive the general pipe condition along the entire length of the test pipe.
    - The AESL ECAT detection rate for the machined defects in one test pit was 100%, detecting six of six of the machined defects within their scan range. On average, AESL located anomalies within a small distance of the recorded defect location. The location

differences could be attributed to differences in the vendor's and the EPA contractor's coordinate reference systems. The ECAT device was used to collect pipe wall data on 0.5% of the test pipe, i.e., 1-m circumferential bands at three locations. In addition to the pipe condition data from the ECAT magnetic flux inspection tool, AESL also collected ultrasonic wall thickness measurements, and coating assessments and soil data (i.e., soil resistivity, redox, pipe-to-soil potential, and pH;) from the three pits. They also collected the soil data from seven other pits along the test pipe. AESL also used an extensive analysis procedure to derive the general pipe condition along the entire length of the test pipe.

- With regard to corrosion pits greater than 50% deep, the ECAT MFL method used by AESL reported for Pit L (Pipe 30), a substantially larger number of corrosion pits greater than the size measured manually after grit blasting. For Pit F, a similar number (5 vs. 3) of corrosion pits greater than 50% deep were identified by both methods. For Pit L, AESL reported that for the 20 deepest pits, 18 of these were greater than 50% deep. The post assessment by EPA's contractor found one deep pit, at 68%, two pits near 50% (i.e., 46% and 47%), and many smaller pits. AESL may or may not remove the corrosion product within natural defects. While done for the first pipe assessed, AESL was asked not to do it for this pipe because this could possibly influence results for subsequent tests in the demonstration. Per AESL, removal or non-removal of corrosion does not affect AESL's calibration or sizing of defects, since the MFL inspection tools are calibrated prior to arrival on site and sizing models are based on a database of defects at AESL. The pipes in Pits 2 were not subjected to detailed assessment after the demonstration, so there is no data for direct comparison with AESL data.

- AESL used models, e.g., stress analysis, fracture analysis, and extreme value statistics, to extrapolate results from three pits for the entire pipe length. AESL estimated that > 65 potential through-wall defects would be present along the pipeline length. For the 2/3 of the pipeline representative of Pit 2 and Pit F, AESL estimated there are potentially 15 through-wall defects and for the 1/3 of pipeline representative of Pit L, there are potentially >50 through-wall defects along the pipeline. The confirmation results are ambiguous regarding AESL's projected number of through-wall holes in the test pipe. The available data from the 12 exhumed, characterized pipes found no through-wall holes, and leak detection studies indicated a maximum of 20 leaks. However, there are insufficient data to eliminate the possibility that a substantial number of through-wall holes, or near- through-wall holes, do exist. For example: (a) since only 12 of 171 (7%) of pipe lengths were measured in detail for wall loss and corrosion pits, the actual number of through-wall holes in the remaining 93% of the test pipe is not known; (b) AESL collected metal loss data on only 0.5% of the test pipe, but they augmented their direct measurements with other relevant data, and then subjected the data to a logical and systematic analysis in order to generate their predictions of potential through-wall defects in the remainder of the pipe, and a comparable assessment was not within the EPA contractors' scope of work; (c) some through-wall holes may be present, but not leak due to plugging; (d) AESL was given 2500-ft as the length of the test pipe, instead of 2057-ft, so this elevated their extrapolated number of potential through-wall holes; the EPA contractor's numbers were extrapolated to 2500-ft for the comparisons above; and (e) the constraint of a multiple vendor demonstration did not permit AESL to decide the location of each excavation, which they would normally decide themselves based on soil tests.

- AESL also conducted a pipeline stress analysis assuming various loading regimes (soil overburden and traffic), membrane and bending stress, structural significance of the corrosion, and fracture mechanics models to predict critical defect sizes for the risk of structural pipeline failure. AESL estimated that > 63 potential critical wall defects existed. For the 2/3 of the pipeline representative of Pit 2 and Pit F, there are potentially 13 critical defects ( >0.57-in.) and for the 1/3 of pipeline representative of Pit L, there are potentially >50 critical defects (>0.67-in.) along the pipeline. Based on the estimated maximum stresses, defect distribution models, and assumed pipe material properties, AESL concluded that defects of sufficient depth to cause structural failure of the pipe may be present. The EPA project scope did not include a critical defect analysis by EPA's contractor, so no direct comparison was possible.

  - A number of factors that can influence AESL's findings were identified. Because detailed pipeline material property data could not be provided to AESL due to the age of the pipeline system, there are uncertainties in the stress analysis and critical defect depth predictions. The identification of a historic American pipe standard for cast iron pipe, as opposed to the British Standard that was used, would allow AESL to reduce the uncertainty in their assessment of original dimensions, material properties, and test pressures. AESL also notes that there may be variations in the soil properties and hence corrosion drivers along the pipeline length, which may affect the validity of the statistical predictions. The fracture mechanics modeling conducted by AESL is based on a singular defect being present at a point of maximum stress to determine critical defects. Defects found in close proximity to each other are likely to give rise to higher stress concentration and therefore a further increase in the risk of structural failure. One excavated pipe location used by AESL was near a large leak, which may have contributed to higher corrosion rates that may have biased the extrapolations towards larger defects. AESL would normally select the assessment points, but the selection options were limited by the test program requirements. Additionally, the sizing software used by AESL is based on calibration scans of flat-bottomed corrosion defects from different pipes of different wall thicknesses and potentially different magnetic properties. As such, this demonstration provides a unique opportunity for AESL to improve their sizing algorithms based on the more complex geometry of natural defects found in the test pipe.
  - The wall thickness data from ultrasonic devices was in good agreement from both AESL and EPA's contractor.
  - The inspection with the ECAT device identified fifteen internal defects. No independent data were collected to confirm the internal metal loss anomalies identified by AESL.

- RSG HSK provided axial and circumferential location of average depth of metal loss anomalies over the 2x2-in. sensor aperture for defects at specific excavation locations. RSG's CAP provided axial and circumferential location of average depth of metal loss anomalies over the 1x1-in. sensor aperture for defects at specific excavation locations. CAP provided local wall thickness values at nominally 250-ft intervals on the top of the pipe and HSK provided full pipe circumference measurements in three locations. These readings did not discover significant metal loss, which therefore indicated a good condition for the pipeline as observed in the 12 exhumed pipes, representing 7% of the test pipe. The HSK and CAP sensor sizes did not provide sufficient resolution to accurately measure the machined defects. HSK and CAP did not inspect where obstacles are encountered, such as valves and joints. However, the HSK can be used to specifically inspect joints if required. This was not attempted as part of the demonstration. While a prototype at the demonstration, a more advanced commercial version of the CAP tool is reported to exist, as is a full circumferential scan capability in a keyhole excavation.

All of the technologies accomplished the first goal of any demonstration, being able to collect data on site, within the time window provided, and analyzing the data to provide results that are consistent with their reported methods and procedures. The generally good condition of the 12 exhumed sections of the test pipe and small range of sizes of pipeline anomalies did not enable a full evaluation of the sensitivity of the individual technologies. Each technology targets a specific market niche, resolution, ease of use and other factors. One conclusion drawn from this study is that the technologies tested would benefit from further calibration to a wider range of excavated pipe data from the field. Also, although all of the exhumed pipes had metal loss, their condition with regard to overall metal loss was generally good. The average wall loss was calculated for each of the 12 exhumed pipes, and highest wall loss observed for a 12-ft length of pipe was 2.6%.

Vendors were provided an opportunity to summarize any advances in tool configuration and performance since the field demonstration in Appendix H to this report. The technologies have, in some cases, been substantially modified since the completion of the field demonstration in September 2009. The most current information about the state of these technologies can be found at:

AESL (http://www.aesengs.co.uk/)

Echologics (http://echologics.com/)

Pressure Pipe Inspection Company (PPIC) (see Pure Technologies)

Pure Technologies
(http://www.puretechltd.com/applications/pipelines/water_wastewater_pipelines.shtml)

Rock Solid Group (http://www.rocksolidgroup.com /Non-Destructive-Testing.aspx)

Russell NDE Systems Inc., (http://www.russelltech.com/; http://www.picacorp.com/).

One key gap is a better understanding of the cost of obtaining data for water main inspections compared to the benefit in terms of reducing failure risks. As novel technologies develop and competition grows, it is anticipated that non-destructive inspections will become more cost-effective even for pipes with moderate consequences of failure. This demonstration involved the collection of cost data in order to help to address this issue. The cost of inspection is dependent on a number of variables including the length and diameter of pipe to be inspected, pipe accessibility, and number of services requested (some vendors offer volume discounts). The cost of an inspection has two main components: (1) the cost of the service provided by the inspection vendor; and (2) the cost for the water company to prepare the line and run the inspection tool, which is often more difficult to quantify.

The estimated inspection costs were developed based upon vendor quotes for inspecting, in 2009, a 10,000 ft section of 24-in. cast iron pipe along the same route as the demonstration site in Louisville, KY. The cost for a wall thickness survey alone ranges from \$3 to \$7/ft; the cost for both leak detection and a pipe wall thickness survey ranges from \$3 to \$9/ft. Cost savings can be achieved when combining the leak detection with pipe wall thickness survey due to reduced time, labor, and equipment costs. The cost for internal inspection is estimated to range from \$15 to \$19/ft and the cost for external inspection is estimated to range from \$3 to \$4/ft. Site-specific factors and technology development will change costs.

The site preparation costs for line modification and field support are highly site-specific and for this reason the estimates provided are order of magnitude estimates based upon typical construction costs. It is estimated that the site preparation costs to conduct a wall thickness survey of 10,000 ft of 24-in. diameter cast iron pipe may range in magnitude from \$0.48/ft to \$0.69/ft (including traffic control, pit/pothole excavation, tapping, backfill, and restoration). It is estimated that site preparation costs for an internal inspection of 10,000 ft of 24-in. diameter cast iron pipe are approximately \$0.58/ft (including traffic control, pit excavation, tapping, backfill, and restoration). It is estimated that site preparation costs for an external inspection of 10,000 ft of 24-in. diameter cast iron pipe may range in magnitude from \$0.94/ft to \$1.63/ft (with 9 to 13 excavated locations, respectively).

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## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| 3D | three-dimensional |
| AC | alternating current |
| A/D | analog-to-digital |
| AESL | Advanced Engineering Solutions, Ltd |
| ANSI | American National Standards Institute |
| BEM | Broadband Electro-Magnetic |
| CAP | Crown Assessment Probe |
| CCTV | closed-circuit television |
| CMM | coordinate-measuring machine |
| DSP | digital signal processor |
| ECAT | External Condition Assessment Tool |
| EPA | U.S. Environmental Protection Agency |
| FAD | failure assessment diagram |
| gpm | gallons per minute |
| GPS | global positioning system |
| HDPE | high density polyethylene |
| HF | high flux |
| HSK | Hand Scanning Kit |
| ksi | kilopounds per square inch |
| ID | inner diameter |
| LWC | Louisville Water Company |
| MGD | million gallons per day |
| MJ | mechanical joint |
| MRRP | Main Replacement and Rehabilitation Program |
| MSD | Municipal Sewer Department |

| | |
|---|---|
| NDE | non-destructive evaluation |
| NDT | non-destructive testing |
| NPT | National Pipe Thread |
| NRC | National Research Council |
| NRMRL | National Risk Management Research Laboratory |
| | |
| OD | outer diameter |
| | |
| PICA | Pipeline Inspection and Condition Analysis Corporation |
| PPIC | Pressure Pipe Inspection Company |
| psi | pounds per square inch |
| PVC | polyvinyl chloride |
| PWA | Pipe Wall Assessment |
| | |
| QA/QC | quality assurance/quality control |
| QAPP | Quality Assurance Project Plan |
| | |
| RFEC | remote field eddy current |
| RF | radio frequency |
| RFT | remote field technology |
| RSG | Rock Solid Group |
| | |
| SBR | SmartBall™ receiver |
| SOTR | State of the Technology Review |
| | |
| TO | Task Order |
| | |
| WERF | Water Environment Research Foundation |
| WTT | Wall Thickness Testing (Sahara®) |

# 1.0: INTRODUCTION

Nine pipe wall integrity assessment technologies were demonstrated on a 76-year-old, 2,057-ft-long portion of a cement-lined, 24-in. cast iron water main in Louisville, KY. This activity was part of a series of field demonstrations of innovative leak detection/location and condition assessment technologies sponsored by the U.S. Environmental Protection Agency (EPA) from July through September 2009. The main goal of the demonstrations was to acquire a snapshot of the current performance capability and cost of these innovative technologies under real-world pipeline conditions so that technology developers, technology vendors, research-support organizations, and the user community can make more informed decisions about the strengths, weaknesses, and need for further advancement of these technologies.

Pipe wall integrity assessment was one part of a comprehensive water pipeline condition assessment demonstration where six inspection companies operated 12 technologies that were at various stages of development and provided different types and levels of leak and/or structural condition data. Technologies were included for wall-thickness screening (i.e., average wall loss over many tens of feet), for detailed mapping of wall thickness, and for leak detection. Both in-line and external inspection technologies were demonstrated. The inspection technologies used visual, mechanical, acoustic, ultrasonic, and electromagnetic methods for acquiring leak and pipe condition data. The inspection results for each technology were compared to the leak rates or dimensions of introduced and/or naturally occurring anomalies, as well as their location along the pipeline.

This report presents the results of a total of nine pipe wall integrity assessment technologies including:

Average wall thickness screening with PPIC[1] Sahara® Wall Thickness Testing (WTT), Pure's SmartBall™, and Echologics'[2] ThicknessFinder;

Inline inspection of the entire pipeline length with PPIC[1] Sahara Video® , which inspected only the inner wall, and two remote field eddy current (RFEC) methods called PPIC[1] PipeDiver® RFEC and Russell[3] NDE Systems Inc. See Snake® Remote Field Technology (RFT), which detect both internal and external metal loss; and

External inspection at selected excavation points using Advanced Engineering Solutions, Ltd. (AESL) External Condition Assessment Tool (ECAT), Rock Solid Group's (RSG) Hand Scanning Kit (HSK), and RSG's Crown Assessment Probe (CAP). Different approaches are used to estimate the condition of the pipe in sections that are not inspected.

Each of the three innovative average wall thickness screening tools demonstrated (and listed in the first bullet above) uses a platform that is also used for an established leak detection technology. The demonstration of the leak detection technologies is described in a companion report (Nestleroth, B. et al., 2012) .

## 1.1 Background

To gain a better understanding of the available technologies for condition assessment of water mains, a Technology Forum was held on September 9 and 10, 2008, in Edison, NJ under Task Order (TO) 62. The

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[1] The Pressure Pipe Inspection Company's (PPIC) is now part of Pure Technologies, Inc.

[2] Echologics is now a subsidiary of Mueller Water Products.

[3] Russell NDE Systems, Inc. has transferred its water and waste water inspection business to its subsidiary: Pipeline Inspection and Condition Analysis Corporation (PICA)

Forum indicated that the state of the art in condition assessment technologies is still developing and that water utilities could benefit from third-party, independent sources of information on the capabilities of innovative inspection technologies. Technology demonstrations on real systems are particularly valued by water utilities and can play a vital role in accelerating the adoption of appropriate, innovative condition assessment technologies. A range of real-life defects and conditions should be present when undertaking these types of demonstrations to maximize the benefit to utilities.

After participating in the Forum, the Louisville Water Company (LWC) offered a section of 24-in. diameter, cement-lined, cast iron pipe for field demonstrations of water main inspection technologies. LWC treats 135 million gallons per day (MGD) of water and transmits water to 270,000 service taps through 3,500 miles of water main ranging in diameter from 1 to 60-in. Under its Main Replacement and Rehabilitation Program (MRRP), the company annually replaces over 35 miles of water mains to maintain the water transmission system. A 2,500-ft portion of 24-in. diameter cast iron transmission water main along Westport Road was scheduled for replacement in September 2009. LWC agreed to make all or part of this pipe available for field demonstrations and provide necessary on-site assistance. A continuous 2057-ft section of the pipe was used for the demonstrations.

The field demonstration occurred between July 6 and September 4, 2009. This program presented an opportunity to (1) apply inspection technologies under nearly normal operating conditions, (2) compare parameter measurements from non-destructive testing (NDT) with direct measurements, and (3) remove sections of the pipe for comparative testing with other technologies at a later date.

Cast iron pipe is the oldest and largest part of the water network (Thomson and Wang, 2009). It is critical that utilities have the capability to undertake reliable condition assessment of cast iron pipes to prevent failures and premature rehabilitation or replacement. Innovative technologies are available for condition assessment of cast iron mains, but limited third-party performance and cost data inhibit their effective consideration by the user community.

The suite of technologies considered for demonstration was based on a state of the technology review report prepared under TO 62 on inspection technologies of water mains for ferrous pipes (Thomson and Wang, 2009) and Forum input. Consistent with the focus of the state of the technology review and the Forum, only leak detection/location and structural condition assessment technologies for ferrous pipes were considered for the field demonstrations. Six vendors providing 12 different technologies including leak detection/location and condition assessment technologies (both internal and external) agreed to participate in the field demonstration program with substantial in-kind support.

The EPA contractor, in coordination with the participating vendors and the LWC, was responsible for the planning, coordination, oversight, and execution of this field demonstration project. The major tasks associated with the field demonstration project are described below:

- ***Task 6.1: Pre-Demonstration Activities***. Pre-demonstration activities included planning and coordination of project activities among EPA, LWC, and participating technology vendors; preparation of a Quality Assurance Project Plan (QAPP); development of test protocols (with vendor input); and communication of project schedules and testing requirements to all project participants.
- ***Task 6.2: Field Demonstration***. EPA's contractor coordinated with the participating vendors and LWC for all on-site demonstration activities, communicated safety requirements, planned/ adjusted test schedules, monitored test progress, and documented field observations. In performing the field demonstration, the technical and quality assurance/quality control (QA/QC) procedures were followed as specified in the EPA-endorsed QAPP.

- ***Task 6.3: Post-Demonstration Evaluation and Reporting***. Post-demonstration activities included exhuming 200+ ft of pipe, shipping the pipe to EPA contractor's lab, preparing pipe segments for wall thickness assessment, and assessing pipe wall thickness both manually and with a laser scanner. In performing the post-demonstration pipe verification, the QA/QC procedures were followed as specified in the addendum to the EPA-endorsed QAPP. This task also included the preparation of technical reports and photo documentation to summarize the results of the field demonstration.

The main goal of the demonstrations was to acquire a snapshot of the current performance capability and cost of these innovative technologies under real-world pipeline conditions so that technology developers, technology vendors, research support organizations, and the user community can make more informed decisions about the strengths, weaknesses, and need for further advancement of these technologies.

The ultimate desired outcome from these demonstrations is to detect problems in large diameter, cast iron water mains prior to their failure, as well as to reduce premature replacement of sound buried water infrastructure. These outcomes are expected to arise, in part, due to expanded and accelerated acceptance and use of effective condition assessment devices, systems, and procedures, and better decisions regarding development and use of innovative condition assessment devices, systems, and procedures.

## 1.2 Organization of Report

This report is divided into five main sections that include introductory material (Section 1.0), summary and conclusions from the results of the field demonstration (Section 2.0), description of the materials and methods used to manage the field demonstration (Section 3.0), description of the materials and methods used to conduct the post-demonstration confirmation study (Section 4.0), and discussion of results provided by each technology vendor (Section 5.0). This report covers acoustic pipe wall assessment, internal inspection, and external inspection. Volume 2 of this report contains appendices with EPA contractor assessment data for excavated pipe plus the vendor inspection reports and vendor letters identifying post-demonstration technology status or changes. A companion report (Nestleroth, B. et al., 2012) covers the demonstration results for the leak detection and location technologies.

# 2.0: SUMMARY AND CONCLUSIONS

The state of the art in condition assessment technologies for water mains is still developing and water utilities are interested in third-party, independent sources of information on the capabilities of innovative inspection technologies. Technology demonstrations with a range of real-life defects and conditions are particularly valuable to water utilities and can play a vital role in accelerating the adoption of appropriate, innovative condition assessment technologies. A field demonstration program was conducted in 2009 to evaluate condition assessment technologies applicable to the inspection of cast iron water mains. All nine condition assessment technologies were demonstrated on a 76-year-old, 2,057-ft-long portion of a straight, cement-lined, 24-in. diameter cast iron water main in Louisville, KY. These technologies included acoustic pipe wall assessment, internal inspection, and external inspection tools. This section provides an overview of the technologies, reviews the complexity of site logistical and operational requirements, summarizes the condition assessment results from each inspection tool, and presents available cost information for inspection and site preparation.

## 2.1 Technology Summary

**Acoustic Pipe Wall Assessment.** The acoustic pipe wall thickness assessment technologies that were demonstrated included the PPIC Sahara® (now part of Pure) Wall Thickness Testing (WTT), Pure SmartBall™ Pipe Wall Assessment (PWA), and Echologics ThicknessFinder. Each of these technologies measures the speed of sound through consecutive sections of the pipeline, and then uses a formula to relate acoustic velocity changes to the wall thickness for the associated length of pipe. While each technology used some form of acoustic device, the implementations were quite different as follows:

- **Sahara® WTT** has a truck-mounted reel of neutrally buoyant cable, and attached near the end of the cable is a small parachute with a hydrophone. The cable is fed into the water main, which is typically under pressure. The parachute-hydrophone-cable assembly is pulled in the direction of flow, and the hydrophone is stopped at intervals (e.g., 33-ft). For each interval a sound pulse is introduced into the pipe, and the pulse arrival time at the hydrophone is determined. The differences in travel times of the acoustic pulses over the consecutive pipe intervals enables acoustic velocity and average pipe wall thickness to be calculated for the associated interval.
- **SmartBall™ PWA** utilizes a non-tethered, in-line sensor to measure the acoustic velocity of sound pulses injected into the pipe. **SmartBall™** is comprised of a spherical, sealed package of electronics for detecting and recording acoustic emissions, position (e.g., rotation, acceleration), and time data. The spherical package is placed inside a foam ball to reduce noise as it moves through the pipeline. The SmartBall ™ is inserted into the pipeline through a special tube while the pipeline is under pressure, then it rolls along the bottom of the pipe until it is captured downstream by a special extraction net that is deployed through another tube. Timed sound pulses from known locations along the pipeline are also used to help determine the location of the SmartBall™ vs. time. Other timed sound pulses are put into the pipe to enable acoustic velocity determinations every 1 to 2 ft. as the SmartBall™ travels the pipe. After the SmartBall™ is retrieved, the time, location, and acoustic emission data are correlated to determine acoustic velocity, to estimate the average effective wall thickness along the pipeline, and to identify anomalous sections.
- **Echologics' ThicknessFinder Technology** uses paired accelerometers mounted on the outside of the pipe at discrete locations to determine travel time of an out-of-bracket sound from one transducer to the other. This enables the acoustic velocity to be determined and the effective average wall thickness to be calculated for the associated pipe interval. In the demonstrations the

distance between sensors ranged from 250 to 360 feet per determination of effective wall thickness.

Knowledge of average wall thickness in a pipe section does not identify specific defects, but can be valuable for focusing subsequent, more detailed and expensive structural inspections on the most problematic areas.

**Internal Inspection.** The internal inspection technologies that were demonstrated included the Sahara Video®, PipeDiver® RFEC, and See Snake® RFT. Sahara Video® used closed circuit television (CCTV) to conduct an internal inspection of the pipeline, while PipeDiver® and See Snake® used a form of RFEC technology to conduct the inspection:

- Sahara Video® uses a video camera at the end of a cable tether. The camera, which was inserted and pulled through the pipeline using the water flow, provided real-time, in-service, CCTV inspection of the test pipe. The camera was also tracked by an operator from ground level to mark items of interest on the pavement.
- PipeDiver® RFEC is a non-tethered, free swimming platform for inspection of in-service water mains and includes an electronics module, battery module, and transmitter module for above ground tracking. PipeDiver® is inserted and extracted from the water pipe via large, vertical tubes designed to launch or receive the tool at pipeline pressures.
- See Snake® RFT is designed to be launched in a live pipeline. However, the demonstrated tool was a tethered prototype unit designed to be pulled through a dry line. This prototype was customized for the demonstration in order to adapt the technology to a 24-in. diameter line. The hard diameter of the tool is smaller than the inner diameter (ID) of the pipe to allow for passage around protrusions, lining, and scale within the pipe.

**External Inspection.** The AESL ECAT, RSG HSK and RSG CAP external inspection technologies were demonstrated on the same cast iron water main in Louisville, KY as described above.

- AESL attaches the ECAT system to the exterior of the pipe using high strength magnets. The ECAT is manually operated and uses magnetic flux leakage (MFL) technology to locate and size defects. ECAT only scans a portion of the exposed pipe at one time and then must be repositioned. This process continues until the entire circumference and length of the exposed pipe has been scanned. The ECAT system is used in combination with commercial ultrasonic instruments, visual inspection of coating condition, and soil properties to statistically predict the condition of long lengths of un-inspected pipe from the results of the few local inspections.
- RSG HSK is a handheld device that uses a patented Broadband Electro-Magnetic (BEM) technology to assess the localized pipeline condition in select excavations. The HSK is manually moved around the exposed pipe in a grid pattern to collect pipe defect data (e.g., remaining wall thickness, areas of metal loss, and fractures). The HSK system is designed to inspect the full pipe circumference, or any part of it, along the entire excavated length, dependent on accessibility. The condition of the entire water main segment is inferred from these local measurements.
- RSG CAP also uses the BEM technology, but it is used for keyhole inspections. The device operates with a down-hole, clamp-on device to affix the sensors to the pipe. The CAP system is only designed to scan the top portion of the pipe exposed via the keyhole excavation, and is most suitable for pipes where crown corrosion is a common problem, such as pressure sewer mains. Further developments after the demonstration provide the capability for full-circumference scans, which are more applicable to water mains. The condition of the entire water main segment is then inferred from these local measurements.

## 2.2. Technology Demonstration

Many aspects of these technologies were observed over the course of the demonstration. This included an assessment of logistical and operational requirements in order to assess the feasibility and complexity of use for the various inspection tools. The vendors provided their assessment of the test pipe condition, with some reporting average or effective wall thickness for various spans of pipe; others reporting anomalous pipe segments; and still others reporting the size, depth, and location of specific defects along the test pipe. Pipe segments were then selected for excavation based upon these inspection results and visual assessment of the pipe condition as it was removed. For each technology, inspection results were compared to the dimensions and locations of machined defects and/or naturally-occurring defects to evaluate the performance of the pipe wall integrity assessment technologies. The amount of metal loss was quantified manually or with a laser scanner and compared to the vendor inspection results for these exhumed pipes. Cost estimates to implement the various technologies for the inspection of a 24-in. cast iron pipe were also requested and are documented in this report, along with estimated site preparation costs for those activities typically conducted by the utility.

Based on data collected by EPA's contractor independently of the vendors, a semi-quantitative assessment was made that the pipe was in overall good condition. Twelve lengths of pipe, out of 171 (i.e., 7%) in the full test pipe, were excavated and evaluated off-site by methods described elsewhere in the report. In those twelve pipes, no through-wall pits were found. The cement mortar liner was in good condition, which was considered an indication of minimal inner wall corrosion. The maximum external wall volume loss was 2.6%, with seven pipe lengths at $\leq$ 1% volume wall loss. The deepest pit was 85% of wall thickness. One pipe had 13 pits deeper than 50%; four pipes had between four and six pits >50%; and the other seven had between zero and two pits >50%. The largest pitted area was 25-in. long and 48% deep. A detailed statistical and structural condition assessment of the pipe was not done to, for example, estimate the size and number of critical defects subject to fracture. A conclusive comparison between this semi-quantitative assessment, and direct or extrapolated condition assessments by the vendors was not always possible.

The pipe wall integrity inspection demonstrations did not evaluate technology capability for all types of failure modes. Interior metal loss was not evaluated. The pipe had a cement mortar liner, which appeared to be in good condition based on CCTV and visual observation of excavated pipes. It was assumed that a sound cement liner indicated little or no corrosion in the adjacent pipe wall. Removing the cement mortar liner to assess the inner pipe wall was not within the project scope. Cracks were not a priority, and were not generally present. Significant cracking was not observed in the 12 excavated pipes that were characterized in detail, nor were cracks included in the set of machined defects, nor did the technologies with crack-detection capability report cracks. The leak detection demonstration previously conducted indicated few through-wall cracks. Detection of mis-aligned joints was not a capability of the demonstrated technologies, nor was mis-alignment found during documentation of the pipe characteristics.

Preliminary reports were requested within one week and final reports within five weeks of the demonstration. These vendor reports are an important source of data presented in this summary report. Users of this report can refer to these appendices to review the original format and organization of the inspection data as issued by the individual vendors. The vendor reports are presented in Volume 2 of this report including Appendix B (Sahara® Video, Sahara®WTT, and PipeDiver®), Appendix C (SmartBall™ PWA), Appendix D (ThicknessFinder), Appendix E (See Snake®), Appendix F (ECAT), and Appendix G (HSK and CAP).

Because this demonstration was a snapshot in time, new developments may have taken place since completion of the demonstration. For this reason, the vendors were asked to provide formal comments on this report to highlight advancements since completion of the demonstration and/or clarification on what was reported. These comment letters are contained in Appendix H. Additional technology modifications have occurred since the field demonstration was completed in September 2009. Information about the current state of these technologies can be found at:

AESL (http://www.aesengs.co.uk/)

Echologics (http://echologics.com/)

Pressure Pipe Inspection Company (PPIC) (see Pure Technologies)

Pure Technologies
(http://www.puretechltd.com/applications/pipelines/water_wastewater_pipelines.shtml)

Rock Solid Group (http://www.rocksolidgroup.com /Non-Destructive-Testing.aspx)

Russell NDE Systems Inc. (http://www.russelltech.com/ ; http://www.picacorp.com/).

**2.2.1 Logistical and Operational Requirements**. The logistical and operational requirements encountered during the demonstration were documented and are summarized in the report including the number of technicians needed, any need for operator intervention, the number and spacing of pipe contact points, access requirements, and more. Tracking this information provides insight into the ability of the tools to mobilize, access the pipe, and operate under various field conditions for a 24-in. cast iron pipe. This information will help utilities to gauge the feasibility of using these technologies at their site. Comparison data for the logistical and operational variables encountered during the demonstration are provided in Table 2-1 for the acoustic pipe wall assessment, internal assessment technologies, and external assessment technologies. In addition, further discussion is provided below of the transportation and installation requirements and implementation of the technologies.

**Acoustic Pipe Wall Assessment.** Sahara® WTT and SmartBall™ PWA require internal pipe access, but are minimally-disruptive in nature and can be performed while the pipeline is in service. ThicknessFinder does not require internal pipe access, is non-disruptive, and can be performed on a live main with or without flow. Sahara® WTT required a dedicated truck to handle the cable tether and data-processing equipment; SmartBall™ equipment arrived in seven cases via overnight shipment; and ThicknessFinder equipment arrived at the site in a passenger vehicle with the equipment operator. Installing the Sahara® WTT tethered system was the most complicated operation, requiring a minimum of two technicians, but a third made operations run more smoothly. Deploying and retrieving the SmartBall™ was accomplished with two technicians, while ThicknessFinder could conduct its assessment with one technician. Each vendor was capable of configuring their equipment to inspect the full 2,057 ft of pipe.

**Internal Inspection.** Installing the Sahara Video® tethered system required a minimum of two technicians, but a third made operations run more smoothly. The initial PipeDiver® deployment was slow; however as the demonstration continued and the technicians gained familiarity in the operation, tool deployment and retrieval became more efficient. Three operators were needed to set-up the pipeline for PipeDiver® and another three operators were needed during the actual PipeDiver® inspection. At the time of the demonstration, See Snake® was not yet designed to be launched in a live pipeline. As such a wire line was needed to pull the tool through the dewatered pipeline. See Snake® required 3 operators. Each vendor was capable of configuring their equipment to inspect the full 2,057 ft of pipe.

**External Inspection.** Installing the AESL ECAT system required two technicians, while both the RSG HSK and CAP systems required only one technician. Both AESL and RSG were capable of configuring their equipment to inspect the entire circumference of the exposed pipe as long as there was sufficient clearance for access; however they were not able to take data over the bell-and-spigot joints as part of the pipe segment scan. The capacity to inspect the joints is now reported to exist. The RSG CAP is only designed to scan the top portion of pipe exposed via a keyhole excavation.

## Table 2-1. Comparison Data for the Logistical and Operational Variables

| Logistical and Operational Variables | Acoustic Pipe Wall Assessment Tools | | | Internal Inspection Tools | | | External Inspection Tools | | |
|---|---|---|---|---|---|---|---|---|---|
| | Sahara® WTT | SmartBall™ PWA | ThicknessFinder | Sahara Video® | PipeDiver® | See Snake® | ECAT | HSK | CAP |
| Equipment logistics | Dedicated truck | Overnight shipping | Operator transported two cases | Dedicated truck | Overnight shipping | Overnight shipping | Overnight shipping | Overnight shipping | Overnight shipping |
| Internal access? | Yes | Yes | No | Yes | Yes | Yes | No | No | No |
| Utility preparation | Requires one access point and a controlled flow rate. | Requires two access points and a controlled flow rate. Large off takes on the pipe must be closed. | Requires two access points but can be accomplished with hydrants or common pipeline appurtenances. | Requires one access point and a controlled flow rate. | Two access points and a controlled flow rate. Vertical clearance of 40 ft needed for launch tube. | Demonstrated system required the pipeline to be dewatered and installation of a cable with a winch to pull the tool through the pipeline. | Requires full pipe circumference excavation for full circumference scan | Requires full pipe circumference excavation for full circumference scan | Requires keyhole excavation |
| Number of technicians needed for operation | 2 | 2 | 1 | 2 | 5-6 | 2-3 | 2 | 1 | 1 |
| Pipe access or contact points | One; 6,000 ft max. cable length (2,500 as supplied for LWC); Contact every 250 to 400 ft for sound generation. | Two; Insertion and extraction; Distance depends on flow rate; Pulsers installed approximately every 1,000 ft. | Two per test; Every 300 to 400 ft for condition assessment | One; 6,000 ft max. cable length (2,500 as supplied for LWC); | Two; Distance depends on flow rate | Two; pull distance depends on number of bends. The demonstration was 2,000 ft. | External; equipment moved manually to inspect entire circumference | External; equipment moved manually to inspect entire circumference | External; equipment only scans top of pipe |
| Sterilization of components that contact water | Yes. All components tether cable. | Yes. Ball, launching and catching equipment. | No water contact. Accelerometers mounted on pipe surface. | Yes | Yes | Yes | No | No | No |
| Real-time data | Yes | No | Yes | Yes | No | No | Yes | Yes | Yes |
| Condition assessment | Post-analysis used to assess average wall thickness | Post-analysis used to assess average wall thickness | Post-analysis used to assess average wall thickness | On-site analysis to assess areas with potential defects | Post-analysis off-site used to assess general pipe condition | Post-analysis off-site used to assess metal loss defect sizes and locations | Post-analysis of general pipe condition | Post-analysis of general pipe condition | Post-analysis of general pipe condition |
| On-site report | No | No | No | Yes | No | No | On-site data display | On-site data display | On-site data display |
| Operator intervention | Operator impacts pipe to create noise, sensor indexed at specific intervals | No operator tasks after ball is launched until it is received | Trained technician manually set filters to eliminate site-specific noise | Operator had to walk the line to track tool location | Operator had to walk the line to track tool location | Winch control for speed and distance | Manual process | Manual process | Manual process |

#### 2.2.2 Technology Assessment

**2.2.2 Technology Assessment**. The key to a demonstration of inspection technologies is the presence of anomalies (e.g. a detectable deviation in the pipe material that may or may not be a defect depending on size). Since the presence of corrosion anomalies in the pipe was unknown prior to the demonstration, several local machined metal loss defects were installed at four locations with the intent of ranging in size from simple to difficult to detect and quantify for each inspection vendor, except the average wall thickness screening technologies, which are not intended for this purpose. In this way, the demonstration results could be used to define both the current capability and future challenges for each of the inspection technologies. Calibration defects were provided to the inspection vendors for system verification and calibration to facilitate subsequent analysis and post-processing. The manufactured defect sizes ranged from approximately 1- to 6-in. in length with depths varying between 20% up to 70% wall loss. During installation of these defects several areas of natural corrosion were found in the line. As such, the machined defects were placed so as to not disturb the natural corrosion.

**2.2.2.1 Acoustic Pipe Wall Assessment Technologies.** Sahara® WTT, SmartBall™ PWA, and ThicknessFinder are emerging NDT methods that offer non- or minimally- intrusive options to screen water mains for significant average wall loss. This screening information can help to reduce costs by focusing subsequent, detailed inspection on pipe sections where accelerated deterioration is likely to be occurring. The acoustic pipe wall assessment technologies only identify average changes in wall thickness over a specified pipe length, and therefore are not intended to find individual defects, unless the defect is large enough to cause a significant change in the pipe stress carrying capability. Therefore, the machined anomalies described above were not used for calibrating the acoustic pipe wall assessment technologies. For these technologies, the inspection results were compared with the calculated average wall thickness derived from measurements of exhumed pipe samples by laser technology and manual methods as described in Section 4.0. A summary of the average wall thickness inspection results is provided in Table 2-2.

***Sahara® WTT.*** Sahara® WTT presented the wall thickness measurement as an average wall thickness loss ratio (%) in 33 ft intervals (see Table 2-2). It was noted that by utilizing the tethered Sahara system and being able to stop the hydrophone at precise locations, the Sahara WTT technique could allow flexible distance and selectable intervals for calculating average wall thickness loss. However, if finer intervals (better resolution) are selected, then longer inspection times will occur.

A pipe wall thickness loss of less than 2% is considered nominal. Three pipe sections, 295 to 328 ft, 328 to 361 ft, and 361 to 394 ft, showed the highest wall thickness loss (i.e., >30%). Five sections showed 15% to 30% of wall thickness loss. Eleven pipe sections showed <15% of wall thickness loss. The remaining sections showed nominal loss. However, a wall thickness ratio could not be calculated for several pipe sections (i.e., [230 to 295 ft], [787 to 1,640 ft], and [1,935 to 2,057 ft]) due to reasons such as the close proximity of the internal and external sensors, presence of large air pockets, or the pipeline discharge which masked acoustic activity after 1,935 ft.

Sahara® WTT provided average wall thickness results for pipe sections that included seven of the 12 pipes that were fully assessed by EPA's contractor. For the other 5 pipes, pipeline and inspection variables (e.g., flow noise at discharge) adversely affected data collection and therefore Sahara® WTT was unable to provide results. Of these seven pipes, Sahara® WTT predicted two pipes were in sections with wall loss >30%, three pipes were in sections with wall loss between 15%-30%, and two pipes were in sections with <15% wall loss. In comparison, these same pipes that were fully assessed by EPA's contractor were noted to have limited variation with average wall loss of no more than 2.6% (considered to be nominal wall loss). Therefore, Sahara® WTT conservatively estimated the remaining wall thickness for six of the seven pipe sections (e.g., reported the pipe to have significant wall loss when only minimal wall loss was noted in exhumed pipe). This technology is emerging in status and would benefit from additional vendor experience in correlating results with pipelines of varying degrees of wall loss. Further technology development is needed to improve the accuracy and potentially reduce the amount of over calls.

**Table 2-2. Summary of Acoustic Pipe Wall Assessments' Average Wall Thickness Results by Sahara®WTT, SmartBall™ PWA, and ThicknessFinder**

| Distance from Start (ft) | Exhumed Pipe Condition as Assessed by EPA Contractor[4] | Sahara® Average Wall Thickness Loss Ratio (%) | SmartBall™ Pipe Wall Thickness Assessment | ThicknessFinder Pipe Wall Thickness Assessment |
|---|---|---|---|---|
| 0-17 | Pipe visually assessed as it came out of the ditch. No corrosion or cracking was observed. | N/A | Reduced pipe wall stiffness (14 ft to 63 ft) | Good condition (0 ft to 250 ft) |
| 17-33 | | < 15% | | |
| 33-66 | | Nominal | | |
| 66-98 | | < 15% | Nominal stiffness loss (63 ft to 100 ft) | |
| 98-131 | | Nominal | Reduced pipe wall stiffness (100 ft to 165 ft) | |
| 131-164 | | Nominal | Reduced pipe wall stiffness (100 ft to 165 ft) | |
| 164-197 | | Nominal | Nominal stiffness loss (165 ft to 237 ft) | |
| 197-230 | | 15-30% | | |
| 230-295 | | N/A | Reduced pipe wall stiffness (237 ft to 292 ft) | |
| 295-328 | | > 30% | Nominal stiffness loss (292 ft to 394 ft) | Good condition (250 ft to 510 ft) |
| 328-361 | Pipe 30 (339-351 ft) Minimal average wall loss; minimal pitting | > 30% | | |
| 361-394 | Pipe 32 (363-375 ft) Minimal average wall loss; locally moderate pitting | > 30% | | |
| 394-426 | Pipe visually assessed as it came out of the ditch. No corrosion or cracking was observed. | Nominal | Reduced pipe wall stiffness (394 ft to 465 ft) | |
| 426-459 | | < 15% | | |
| 459-492 | | 15-30% | Nominal stiffness loss (465 ft to 488 ft) | |
| 492-525 | | < 15% | Reduced pipe wall stiffness (488 ft to 535 ft) | |
| 525-558 | | < 15% | | Good condition (510 ft to 810 ft) |
| 558-590 | Pipe 49 (567-579 ft) Minimal average wall loss; locally heavy pitting | < 15% | Reduced pipe wall stiffness (540 ft to 592 ft) | |
| 590-623 | Pipe visually assessed as it came out of the ditch. No corrosion or cracking was observed. | Nominal | Nominal stiffness loss (592 ft to 650) | |
| 623-656 | Pipe 56 (651-663 ft) Minimal average wall loss; locally light pitting | < 15% | Reduced pipe wall stiffness (650 ft to 692 ft) | |
| 656-689 | Pipe 56 (651-663 ft) Minimal average wall loss; locally light pitting | Nominal | Reduced pipe wall stiffness (650 ft to 692 ft) | Good condition (510 ft to 810 ft) |

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[4] Four categories of pipe condition were defined by EPA's contractor ranging from best to worst: minimal, light, moderate, and heavy. See Section 4 for details.

**Table 2-2. Summary of Acoustic Pipe Wall Assessments' Average Wall Thickness Results by Sahara®, SmartBall™ PWA, and ThicknessFinder (Continued)**

| Distance from Start (ft) | Exhumed Pipe Condition as Assessed by EPA Contractor[4] | Sahara® Average Wall Thickness Loss Ratio (%) | SmartBall™ Pipe Wall Thickness Assessment | ThicknessFinder Pipe Wall Thickness Assessment |
|---|---|---|---|---|
| 689-722 | Pipe 61 (711-723 ft)<br>Minimal average wall loss; locally moderate pitting | 15-30% | Reduced pipe wall stiffness (650 ft to 692 ft) | |
| 722-754 | Pipe 63 (735-747 ft)<br>Minimal average wall loss; locally heavy pitting<br>Pipe 64 (747-759 ft)<br>Minimal average wall loss; locally heavy pitting | 15-30% | Reduced pipe wall stiffness (742 ft to 770 ft) | |
| 754-787 | Pipe 64<br>(747-759 ft)<br>Minimal average wall loss; locally heavy pitting | Nominal | Reduced pipe wall stiffness (742 ft to 770 ft) | |
| 787-821 | Pipe 69<br>(809-821 ft)<br>Minimal average wall loss; locally moderate pitting | No assessment provided | Reduced pipe wall stiffness (794 ft to 808 ft) | |
| 821-950 | Pipe visually assessed as it came out of the ditch. No corrosion or cracking was observed. | | Reduced pipe wall stiffness (900 ft to 950 ft) | Good with possibly higher corrosion rate (810 ft to 1080ft) |
| 950-1034 | | | Reduced pipe wall stiffness<br>(990 ft to 1,034 ft) | |
| 1034-1174 | Pipe 98 (1162-1174 ft)<br>Minimal average wall loss; locally light pitting | | No assessment provided | |
| 1174-1439 | Pipe visually assessed as it came out of the ditch. No corrosion or cracking was observed. | | | Good with possibly higher corrosion rate (1080 ft to 1439 ft) |
| 1439-1640 | Pipe 137 (1630-1642 ft)<br>Minimal average wall loss; locally light pitting | | | Good condition (1439 ft to 1750) |
| 1640-1673 | Pipe 137 (1630-1642 ft)<br>Minimal average wall loss; minimal pitting | Nominal | No assessment provided | Good condition (1439 ft to 1750) |
| 1673-1706 | Pipe visually assessed as it came out of the ditch. No corrosion or cracking was observed. | Nominal | | |
| 1706-1738 | Pipe 144<br>(1724-1750 ft)<br>Minimal average wall loss; locally light pitting | < 15% | | |
| 1738-1771 | Pipe 144<br>(1724-1750 ft)<br>Minimal average wall loss; locally light pitting | < 15% | | Good with possibly higher corrosion rate (1750 ft to end) |
| 1771-1804 | Pipe visually assessed as it came out of the ditch. No corrosion or cracking was observed. | < 15% | | |
| 1804-1837 | | < 15% | | |
| 1837-1870 | | Nominal | | |
| 1870-1902 | | Nominal | | |

**Table 2-2. Summary of Acoustic Pipe Wall Assessments' Average Wall Thickness Results by Sahara®, SmartBall™ PWA, and ThicknessFinder (Continued)**

| Distance from Start (ft) | Exhumed Pipe Condition as Assessed by EPA Contractor[4] | Sahara® Average Wall Thickness Loss Ratio (%) | SmartBall™ Pipe Wall Thickness Assessment | ThicknessFinder Pipe Wall Thickness Assessment |
|---|---|---|---|---|
| 1902-1935 | | 15-30% | | |
| 1935-2057 | Pipe 166<br>(1978-1990 ft)<br>Minimal average wall loss; minimal pitting | No assessment provided | | |

***SmartBall™ PWA.*** SmartBall™ PWA made measurements every two ft; lengths of degraded pipes were reported in ranges from 14 to 102 ft. SmartBall™ PWA reported the wall thickness assessment results as pipe intervals of interest with reduced wall stiffness for the first 1,050 ft of the test pipe. It had difficulties assessing the second half of the test pipe potentially due to the large amount of noise generated by the water discharge. The data suggested that several interesting variations existed in the apparent pulse velocity at different points along the pipeline. However, it was unclear whether the data revealed actual changes in the hoop stiffness of the pipe wall, or if the data had been affected by the presence or condition of the mortar lining or other pipe stiffness enhancements (such as previous repairs on the pipe). This is a common issue for acoustic-based technologies. In addition, the PWA was able to detect pipeline features such as valves and joints. For example, the acoustic profile showed the locations of the joints at 12-ft intervals. The spatial resolution of the tool is related to the flow velocity and was about one data point every two ft along the line. This technique is not designed to detect individual pits, but may reveal areas where clusters of pitting or thinning produce weakening over several feet along the pipe.

SmartBall™ PWA provided results for approximately the first half of the test section, which included seven of the 12 pipes that were fully assessed by EPA's contractor. For the other five pipes, which were in the second half of the pipeline, inspection variables (e.g., flow noise at discharge) adversely affected data collection and therefore SmartBall™ PWA was unable to provide results. Of these seven pipes, SmartBall™ PWA identified four pipes that were located within regions of reduced stiffness and three pipes that were located within regions where the pipe was considered to have only nominal changes to stiffness (e.g., normal condition).

While none of the exhumed pipes contained a large amount of metal loss, three of the pipes that EPA's contractor identified as more corroded were identified as having reduced wall stiffness by SmartBall™ PWA. These three pipes had either had a larger volume of metal loss or larger area of corrosion with deep pits as identified by EPA's contractor. The fourth pipe identified with reduced wall stiffness by SmartBall™ PWA was later determined by EPA's contractor to have a low volume loss and relatively moderate pitting.

Two of the three pipes identified as normal by SmartBall™ PWA were later confirmed to have minimal volume loss and only a few deep pits. One of the three pipes identified as normal by SmartBall™ PWA had increased volume loss over a large area, but none of the pit depths exceeded 40%.

Although all of the exhumed pipes had minimal average wall loss, SmartBall™ PWA was able to indicate which pipe segments were in worse condition based upon local corrosion pitting. This was a very early use of this emerging technology and tool performance could be improved with further calibration to excavation information from the field.

***ThicknessFinder.*** Echologics' ThicknessFinder had the coarsest resolution with seven readings provided for the 2,057 ft pipe. Numerical values of thickness were provided, along with a qualitative description of the pipe condition. ThicknessFinder reported the wall thickness results as the remaining equivalent thickness of the pipe, which also accounts for the presence of the cement lining. Since the cement lining enhanced the structural stiffness of the pipe, the equivalent thickness of a metallic pipe without the lining, was generally thicker than that of the base metal. The 2,057 ft long test pipe was divided into seven sections, each ranging in length from approximately 250 to 360 ft. The results of the condition assessment measurements indicated six sections in a row with remaining equivalent thickness greater than 0.70-in. with the seventh section just .01-in. below, at 0.69-in. Echologics concluded that although there may be some deterioration in these sections, the pipe is in good structural condition, which they define as having wall loss in the 10%-20% range. They more specifically estimated the effective wall thickness loss to be approximately 14%-20%, which is more severe deterioration than the maximum average wall loss of 2.6% found in the 12 pipe sections assessed in detail.

Echologics provided results for the entire pipe length used in the demonstration. ThicknessFinder provided average wall thickness values over 250 to 360 ft intervals. ThicknessFinder is not intended to be able to discriminate between slight variations in the condition of locally degraded pipe.

**2.2.2.2 Internal Inspection Technologies.** Internal inspection technologies were evaluated based upon detection of natural corrosion areas and existing anomalies or defects. In addition, the electromagnetic inspection devices' ability to detect machined metal loss defects was evaluated.

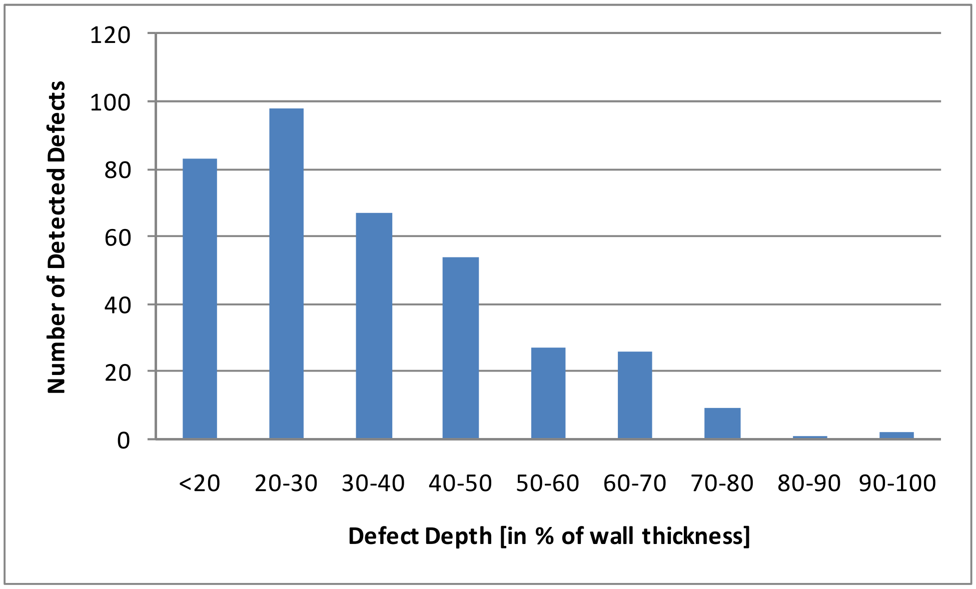
***Sahara® Video.*** Sahara Video® presented the results of the video inspection as a sequence of observations of only the internal surface of the test pipe. Several visible features were identified over the length of the test pipe including outlets (branch connections, hydrants, etc.), air pockets, and corrosion. Two fairly large areas of internal corrosion were found at 1,565 ft and 1,637 ft, but were not independently verified. Sahara Video® provided results that confirmed that the pipe lining was in generally good condition and had minimal degradation or delamination. Air pockets, ranging from small to large in size, were also discovered during the video inspection, but could not be further verified as the air pockets dissipated with flow. However, one week later, one of the leak detection systems being demonstrated also noted that air pockets were present. No debris or tuberculation was found in the pipe. This inspection was a valuable part of the demonstration as it was the first assessment of the ID of the pipe and provided some assurance that subsequent internal condition assessment methods could be successfully applied since an unobstructed path was available from end to end. Sahara Video® only provides information about the condition of the pipe behind the liner if a pipe defect manifests itself on the inside of the pipe visible via video.

***PipeDiver®.*** The PipeDiver® RFEC results showed joint signals, known features and anomalous signals, which were reportedly due to wall thickness loss. Forty-one of a total of 170 pipe segments showed anomalous signals; the size of the anomalies was not quantified. Of the anomalous pipe segments, 14 were identified in the first half of the test pipe, while 27 were identified in the second half of the test pipe.

PipeDiver® testing was conducted as a pilot project to obtain field data for analysis and technology improvements. PipeDiver® provided results for the entire pipe length used in the demonstration. Forty-one of the 172 pipe lengths (24%) were identified as being anomalous. Of the 12 exhumed pipes, one pipe length with the largest area of local corrosion pitting was identified as anomalous. Of the 12 exhumed pipes, five that were assessed and showed minimal degradation were correctly identified as not degraded by PipeDiver®. The remaining six exhumed pipes that were determined by EPA's contractor to be in a more degraded condition were not identified as anomalous by PipeDiver®.

This is an emerging technology, and further verification and calibration data are needed by the vendor to fully assess the nature of these anomalous signals and to improve the ability of the tool to more accurately characterize pipeline condition. The detection and sizing sensitivity of PipeDiver® is limited by the number of sensor channels. This was the first use of PipeDiver® for a cast iron water main; the vendor reported that future developments will focus on improving the detectors and their placement (including increasing the number of available detectors). In addition, the analysis process will be reviewed for new techniques and improved software.

***See Snake®.*** The See Snake® detected 367 wall loss indications. Figure 2-1 shows that a majority of the defects are less than or equal to 50% deep, with a much smaller group in the 60% to 80% range, and only a few defects 90% or deeper. More importantly, the results from See Snake® show that the deep defects are concentrated within the first half of the line, leaving about half of the line with approximately original wall thickness.



(Courtesy of Russell NDE Systems Inc.)

**Figure 2-1. Defect Histogram**

Russell NDE Systems Inc. See Snake® provided detailed results for the entire pipe length examined in the demonstration. Of the 12 exhumed pipes that underwent assessment by the EPA contractor, the pipes with the largest number of metal loss indications were also reported by See Snake® to have a large number of pits. Additionally, the pipes that showed minimal degradation in the detailed examinations were also correctly identified by See Snake® as having few or small anomalies.

Of all of the condition assessment technologies demonstrated, See Snake® provided the most detailed results for the entire pipe length. The total number of corrosion pits, as well as corrosion pit location with respect to the pipe joint and clock position, were reported. The inspection results were found to correlate with the post-demonstration assessment of the 12 exhumed pipe segments. The comparison approach is described in Section 4. It should be noted that the implementation was intrusive, as the pipe had to be cut, a pull cable had to be threaded from start to finish, and the pipe drained for this demonstration inspection.

***Detection of Anomalies-Comparison of See Snake® and PipeDiver® Results***. See Snake® provided detailed results that correlated well with the post-demonstration assessment of the 12 exhumed pipe segments. The total number of corrosion pits, as well as corrosion pit location with respect to the pipe joint and clock position, were reported. PipeDiver® indicated only the pipe length locations where the pipe had anomalies. A summary of the internal inspection results reported by PipeDiver® and See Snake® is provided in Figure 2-2.

From this comparison, it is evident that See Snake® found a much larger number of defects in the first half of the test pipe with some locations corresponding to anomalous pipe found by PipeDiver®. On the other hand, PipeDiver® found a greater number of anomalous pipe segments in the second half of the test pipe, while See Snake® found far fewer and less severe anomalies. Verification of anomalies in specific pipe samples using wall thickness measurements by EPA's contractor for selected pipe segments showed some pitting, but generally the pipe was in good condition. See Snake® provided the most detailed inspection results for the entire pipe length and the condition reported by See Snake® was found to correlate with the post-demonstration assessment of the 12 exhumed pipe segments by EPA's contractor. The bell and spigot joints could be seen in the raw data, but not characterized in detail. Eight joints were identified as anomalous. Due to magnetic permeability noise, See Snake® was not able to characterize any of the machined calibration or test defects. The vendor identified four potential causes of the interference arising from either the installation process for the artificial defects or the previous operation of other electromagnetic inspection devices in the vicinity.

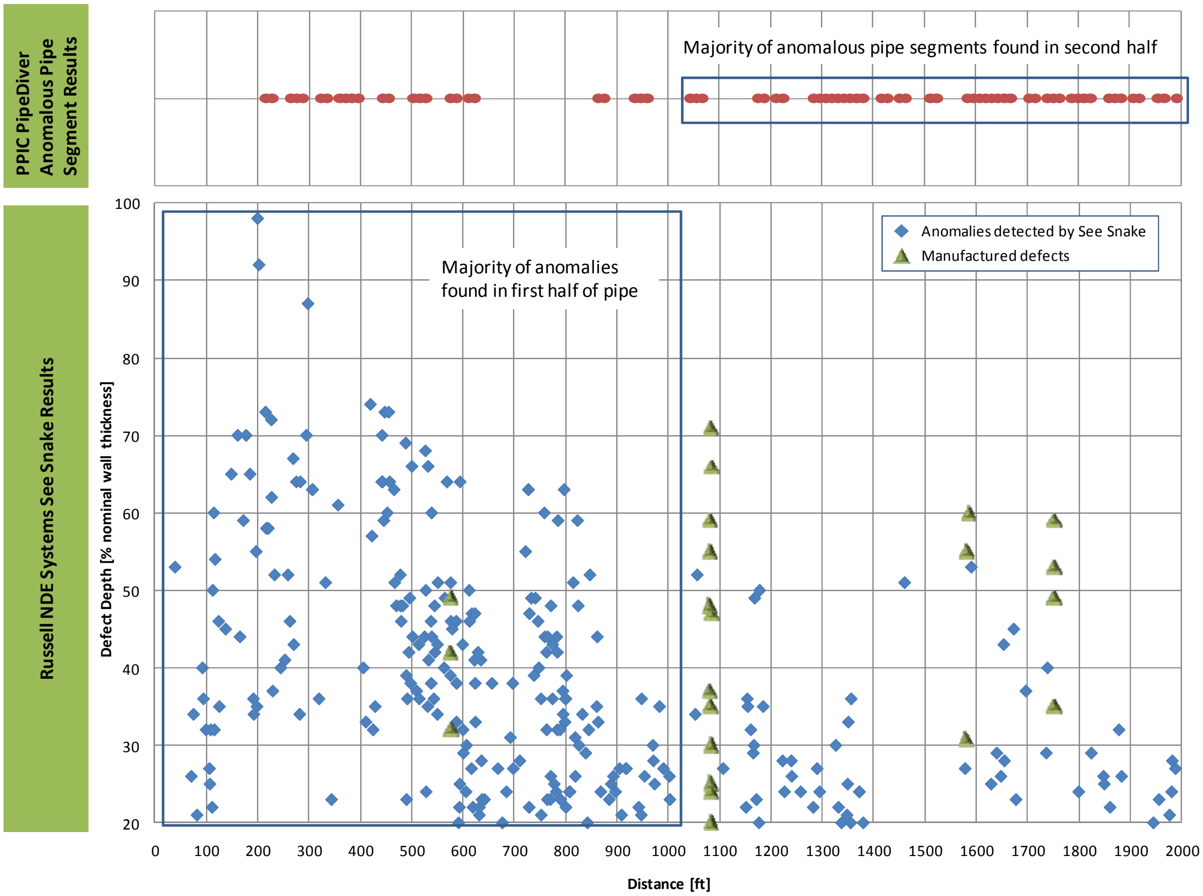


**Figure 2-2. Defect Scatter Graph for See Snake® vs. Anomalous Pipe Locations for PipeDiver®**

**2.2.2.3 External Inspection Technologies.** The same machined metal loss defects as described above were used for the external inspection technology demonstration, along with natural corrosion areas. Each external condition assessment tool found a large number of anomalies in the excavated pipeline sections.

***AESL ECAT.*** AESL's ECAT detected and characterized machined defects. AESL also used an extensive analysis procedure to derive the general pipe condition along the entire length of the test pipe. While on site, AESL conducted assessments of the relative soil corrosivity, pipe coating condition, pipe wall thickness, and full circumference ECAT scans for three excavation locations (labeled as Pit L, Pit 2, and Pit F). AESL integrated and analyzed this data to determine the pipe condition in these three excavated pits. Subsequent statistical analyses were then performed to predict the condition of the un-inspected portions of the pipeline based upon the detailed findings within the excavated pits.

The AESL ECAT MFL device successfully detected six of six machined defects. The measured defect depths ranged from 0.13-in. to 0.53-in. with the ECAT device reporting -47% to + 96% of the measured depths. The measured defect lengths ranged from 1-in. to 3.7-in. with the ECAT device reporting -45% to +210% of the measured lengths. On average, AESL located anomalies within a small distance (2.6 inches) of the recorded defect location, but this apparent error may be attributed to differences between AESL's and EPA contractor's coordinate reference systems.

AESL's analysis of external defects and other data indicated >65(5) potential through-wall defects and >63(6) critical defects. The 2/3 of the pipeline representative of Pits 2 and F likely has 15 through-wall defects and 13 critical defects (≥0.57-in.). The 1/3 of the pipeline representative of Pit L likely has >50 through-wall defects and > 50 critical defects (≥ 0.67-in.). Based on the estimated maximum stresses, defect distribution models, and assumed pipe material properties, AESL concluded that defects of sufficient depth to cause structural failure of the pipe may be present.

While there are some indications that AESL's estimate of >65 potential through-wall holes may be a significant overestimate, a definite conclusion about the accuracy of the estimate is not possible with available data. Indicators that an estimate of >65 through-wall holes is high are: (a) no through-wall defects were found in the 144-ft (i.e., 7% of actual test pipe length) that was sandblasted and evaluated in detail; and (b) the leak detection phase of the study (Nestleroth, B. et al., 2012), reported approximately 8 possible through-wall leaks/1000 ft, which, assuming a uniform leak density across the pipe, projects to 20 through-wall leaks over 2500-ft. However, there are insufficient data to eliminate the possibility that a substantial number of through-wall holes, or near- through-wall holes, do exist. For example: (a) since only 12 of 171 (7%) of pipe lengths were measured in detail for wall loss and corrosion pits, the actual number of through-wall holes in the remaining 93% of the test pipe is not known; (b) AESL collected metal loss data on only 0.5% of the test pipe, but they augmented their direct measurements with other relevant data, and then subjected the data to a logical and systematic analysis in order to generate their predictions of through-wall defects in the remainder of the pipe, and a comparable assessment was not within the EPA contractors' scope of work; (c) some through-wall holes may be present, but not leak due to plugging; and (d) AESL was given 2500-ft as the length of the test pipe, instead of 2057-ft, so this elevated their extrapolated number of potential through-wall holes; the EPA contractor's numbers were extrapolated to 2500-ft for the comparisons above.

AESL also conducted a pipeline stress analysis assuming various loading regimes (soil overburden and traffic), membrane and bending stress, structural significance of the corrosion, and fracture mechanics models to predict critical defect sizes for the risk of structural pipeline failure. AESL estimated the likely number of critical defects in the same pipeline locations. For 2/3 of the pipeline representative of Pit 2 and Pit F, there are potentially 13 critical defects (0.57-in. deep) and for the 1/3 of the pipeline

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[5] This number is somewhat inflated due to AESL being given 2500-ft as the test pipe length instead of 2057-ft.

representative of Pit L, there are potentially >50 critical defects (0.67-in. deep) along the pipeline. Based on the estimated maximum stresses, defect distribution models, and assumed pipe material properties, AESL concluded that defects of sufficient depth to cause structural failure of the pipe may be present. The critical defect depth at the location of maximum stress for Pits L, 2 and F was reported at 0.67, 0.57, and 0.62 in., respectively. Data are summarized in Table 2-3. The project scope did not include a similar level of analysis by EPA's contractor, so no comparison of the number of critical defects was conducted. Also, since the project is focused on the innovative pipe wall integrity measuring devices, EPA contractor's scope did not include an assessment comparable to AESL's assessment of soil characteristics or coating condition; nor did they perform modeling, statistical, or structural analyses to integrate and extrapolate indirect and direct data into a condition assessment for the full length of the test pipe.

Under the demonstration program requirements, the ECAT MFL method used by AESL reported, in one case (Pit L; Pipe 30), a substantially larger number of corrosion pits greater than the size measured manually after grit blasting; and for Pit F, a similar number (5 vs. 3) of corrosion pits greater than 50% deep. For Pit L, AESL reported that for the 20 deepest pits, 18 of these were greater than 50% deep. The post assessment by EPA's contractor found one deep pit, at 68%, two pits near 50% (i.e., 46% and 47%), and many smaller pits. AESL may or may not remove the corrosion product within natural defects. While done for the first pipe assessed, AESL was asked not to do it for this pipe because this could possibly influence results for subsequent tests in the demonstration. Per AESL, removal or non-removal of corrosion does not affect AESL's calibration or sizing of defects, since the MFL inspection tools are calibrated prior to arrival on site and sizing models are based on a database of defects at AESL. The pipes in Pit 2 were not subjected to detailed assessment after the demonstration, so there is no data for direct comparison with AESL pit depth data.

A number of factors that can influence AESL's findings were identified. Because detailed pipeline material property data could not be provided to AESL due to the age of the pipeline system, there are uncertainties in the stress analysis and critical defect depth predictions. The identification of a historic American pipe standard for cast iron pipe, as opposed to the British Standard that was used, would allow AESL to reduce the uncertainty in their assessment of original dimensions, material properties, and test pressures. AESL also notes that there may be variations in the soil properties and hence corrosion drivers along the pipeline length, which may affect the validity of the statistical predictions. The fracture mechanics modeling conducted by AESL is based on a singular defect being present at a point of maximum stress to determine critical defects. Defects found in close proximity to each other are likely to give rise to higher stress concentration and therefore a further increase in the risk of structural failure. One excavated pipe location used by AESL was near a large leak, which may have contributed to higher corrosion rates that may have biased the extrapolations towards larger defects. AESL would normally select the assessment points, but the selection options were limited by the test program requirements. Additionally, the sizing software used by AESL is based on calibration scans of flat-bottomed corrosion defects from different pipes of different wall thicknesses and potentially different magnetic properties. As such, this demonstration provides a unique opportunity for AESL to improve their sizing algorithms based on the more complex geometry of natural defects found in the test pipe.

The wall thickness data from ultrasonic devices was in good agreement from both AESL and EPA's contractor.

The inspection with the ECAT device identified fifteen internal defects. No independent data were collected to confirm the internal metal loss anomalies identified by AESL.

AESL's approach does not require entry into the pipe or disruption of flow. Only selected locations along the pipe require excavation. The ECAT is equipped with GPS and blue tooth technology to enable data transfer in real-time.

***RSG HSK and CAP***. For RSG, the results generally indicate that there is metal loss in the sections of pipe scanned during the demonstration. RSG did not find a common wall thinning trend for the entire pipeline length and indicated that the trends appeared to be section specific. The minimum wall thickness recorded was 0.627-in. in Pit C. A summary of the results is provided in Table 2-4.

RSG only provided relative wall thinning data averaged over the sensor area (1x1 in. for CAP and 2x2 in. for HSK) and therefore did not offer the sensitivity needed to size the machined defects, which were smaller than the sensor area. Therefore, only general observations can be made regarding possible increased wall thinning in the location of the machined defects. The HSK scan of Pit F, which contained fairly large machined defects (35% to 59% wall loss over a 6-in. length and 1-in. wide), did indicate areas of reduced wall thickness over a 6-in. length near the crown of the pipe. However, since the results were averaged there is not sufficient granularity to directly compare the scans with the actual depths of the machined defects in Pit F where RSG reported a minimum wall thickness of 0.678-in. (and the measured minimum of the machined defects was approximately 0.3-in.).

The RSG HSK and CAP results compared well with the general condition of the pipe. The method provided local wall thickness values at nominally 250 ft intervals on the top of the pipe and full pipe circumference measurements in three locations. These readings did not discover significant metal loss that would indicate that the condition of the pipe was less than serviceable.

**Table 2-3. Summary of Condition Assessment Results for AESL ECAT**

| Location [ft] | Exhumed Pipe Condition as Assessed by EPA Contractor[6] | Soil Corrosivity | ECAT Pipe Wall Thickness | Coating Condition ( ° from Top) | ECAT Condition Assessment Results |
|---|---|---|---|---|---|
| 338 (Pit L) | ∗ Minimal average wall loss; Deepest pit 0.53 in.; Avg. wall thickness was 0.76 in. | ∗ Fairly Corrosive<br>∗ AFNOR Score = 7 | ∗ Avg. wall thickness was 0.74 in. | ∗ Generally good with an overall area of coating failure of 6%.<br>∗ Coating between 245° and 278° is in the worst condition with the highest % coating failure at 31% at 278° | ∗ ~330 external defects (Deepest was 0.57 in.)<br>∗ ~3 internal defects (deepest was 0.41 in.)<br>∗ Excavator or mechanical damage at ~90° and between 180° and 280° |

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[6] Four categories of pipe condition were defined by EPA's contractor ranging from best to worst: minimal, light, moderate, and heavy. See Section 4 for details.

| Location [ft] | Exhumed Pipe Condition as Assessed by EPA Contractor[6] | Soil Corrosivity | ECAT Pipe Wall Thickness | Coating Condition ( ° from Top) | ECAT Condition Assessment Results |
|---|---|---|---|---|---|
| 1,080<br>(Pit 2) | ∗ Machined defects – not sandblasted for natural anomalies<br>Deepest pit 70% (0.55 in.);<br>Avg. wall thickness not measured. | ∗ Fairly Corrosive<br>∗ AFNOR Score = 5 | ∗ Avg. wall thickness was 0.73 in. | ∗ Generally poor with an overall area of coating failure of 70%.<br>∗ Coating between 115° and 245° (bottom) is in the worst condition with several axial locations having 100% coating failure. | ∗ ~225 external defects (deepest was 0.59 in.)<br>∗ ~11 internal defects (deepest was 0.41 in.) |
| 1,750<br>(Pit F) | ∗ Minimal average wall loss; Deepest pit 0.37 in.; Avg. wall thickness was 0.77 in. | ∗ Highly Corrosive<br>∗ AFNOR Score = 9 | ∗ Avg. wall thickness was 0.75 in. | ∗ Generally good with an overall area of coating failure of 11%<br>∗ Coating between 147° and 295° is in the worst condition with the highest % coating failure at 39% at 229° | ∗ ~240 external defects (deepest was 0.49 in.)<br>∗ ~9 internal defects (deepest was 0.39 in.)<br>∗ Mechanical damage between 180° and 270°; likely not to have occurred recently |

**Table 2-4. Summary of Condition Assessment Results for RSG**

| Location [ft] | Exhumed Pipe Condition as Assessed by EPA Contractor[7] | Type of Scan | RSG Minimum Wall Thickness [in.] | RSG Average Wall Thickness [in.] | RSG Condition Assessment Results |
|---|---|---|---|---|---|
| 250 (Pit A) | Not assessed | CAP | 0.662 | 0.737 | ∗ Moderate corrosion near the pipe crown |
| 338 (Pit L) | Minimal average wall loss; locally light pitting | HSK | 0.654 | 0.735 | ∗ Higher degree of wall thinning near the pipe crown<br>∗ Moderate degree of wall thinning at the pipe sides<br>∗ 90% of the pipe was examined. 5% could not be scanned due to access restrictions; 5% could not be analyzed for two sections due to noise detected during post-analysis. |
| 510 (Pit B) | Not assessed | CAP | 0.680 | 0.719 | ∗ Moderate corrosion near the pipe crown |
| 809 (Pit C) | Minimal average wall loss; locally moderate pitting seen on site | CAP | 0.627 | 0.703 | ∗ Most severe corrosion near the pipe crown |
| 1,080 (Pit 2) | Machined defects – not sandblasted for natural anomalies | HSK | 0.688 | 0.735 | ∗ Moderate to severe corrosion on the southern side of the pipe<br>∗ Moderate corrosion at the bottom of the pipe |
| 1,173 (Pit D) | Not assessed | CAP | 0.666 | 0.689 | ∗ Moderate corrosion near the pipe crown |
| 1,439 (Pit E) | Not assessed | CAP | 0.704 | 0.709 | ∗ Negligible wall thickness variation |
| 1,750 (Pit F) | Minimal average wall loss; locally light pitting | HSK | 0.678 to 0.711 | 0.745 to 0.748 | ∗ Higher degree of wall thinning near pipe crown<br>∗ Moderate degree of wall thinning at the pipe sides; more prevalent on northern side<br>∗ Thinning in isolated areas; therefore likely due to pitting clusters or graphitization |

## 2.3. Costs

One key gap is a better understanding of the cost of obtaining data for water main inspections compared to the benefit in terms of reducing failure risks. As novel technologies develop and competition grows, it is anticipated that non-destructive inspections will become more cost-effective even for pipes with moderate consequences of failure. This demonstration involved the collection of cost data in order to help to address this issue.

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[7] Four categories of pipe condition were defined by EPA's contractor ranging from best to worst: minimal, light, moderate, and heavy. See Section 4 for details.

The cost of inspection is dependent on a number of variables including the length and diameter of pipe to be inspected, pipe accessibility, and number of services requested (some vendors offer volume discounts). The cost of an inspection has two main components: (1) the cost of the service provided by the inspection vendor; and (2) the cost for the water company to prepare the line and conduct the inspection, which is often more difficult to quantify. Table 2-5 summarizes the estimated inspection costs and site preparation costs for the acoustic pipe wall surveys, internal inspection technologies, and external inspection technologies. The cost of inspection is also likely to change as inspection technology develops.

The estimated inspection costs were developed based upon vendor quotes for inspecting 10,000 ft of 24-in. cast iron pipe along the same route as the demonstration site in Louisville, KY. The cost for a wall thickness survey ranges from $3 to $7/ft; the cost for both leak detection and pipe wall thickness survey ranges from $3 to $9/ft. Cost savings can be achieved when combining the leak detection with pipe wall thickness survey to reduce time, labor, and equipment costs for inspection. The cost for internal inspection is estimated to range from $15 to $19/ft and the cost for external inspection is estimated to range from $3 to $4/ft.

The site preparation costs for line modification and field support are highly site-specific and for this reason the estimates provided are order of magnitude estimates based upon typical construction costs (RSMeans, 2011). The actual site preparation costs for a given site will depend upon regional costs for construction labor, along with factors such as the access requirements, availability and condition of existing hydrants/valves, length of deployment, days on site, and more. It is estimated that the site preparation costs to conduct a wall thickness survey of 10,000 ft of 24-in. diameter cast iron pipe may range in magnitude from $0.48/ft to $0.69/ft (including traffic control, pit/pothole excavation, tapping, backfill, and restoration). It is estimated that site preparation costs for an internal inspection of 10,000 ft of 24-in. diameter cast iron pipe is approximately $0.58/ft (including traffic control, pit excavation, tapping, backfill, and restoration). It is estimated that site preparation costs for an external inspection of 10,000 ft of 24-in. diameter cast iron pipe may range in magnitude from $0.94/ft to $1.63/ft (with 9 to 13 excavated locations, respectively).

## 2.4 Conclusions and Research Needs

The outcome of this demonstration is to provide water utilities with third-party, independent sources of information on applying selected innovative condition assessment technologies for cast iron water mains. Observations are summarized here on the maturity of these technologies for the inspection of cast iron water mains, the complexity of logistical and operational requirements, overall technology performance in predicting pipe condition, and technology costs.

Table 2-5 summarizes useful information on implementation factors, technology inspection results, and costs. In addition, conclusions can be drawn regarding further research and technology development needs and improved methodologies for evaluating pipe wall condition inspection technologies as discussed below.

## Table 2-5. Summary of Implementation Factors, Format of Inspection Results, and Costs

| Technology | Implementation Factors | | | | Format of Inspection Results | | | Cost Factors | |
|---|---|---|---|---|---|---|---|---|---|
| | Diameter Range | Internal/ External | Flow Requirements | Inspection Interval | Provides General Assessment? | Finds Specific Defects? | Provides Detailed Measurements? | Inspection Cost | Site Preparation Cost |
| Acoustic Pipe Wall Assessment | | | | | | | | | |
| Sahara® WTT | >4 in. | Int. | >1 ft/s | Variable. Demonstrated at 33 ft. | Yes | No | No | $3.30/ft | $0.66/ft |
| SmartBall™ PWA | >6 in. | Int. | >0.5 ft/s | Data every 2 feet. Sections of pipe grouped. | Yes | No | No | $6.00/ft | $0.69/ft |
| ThicknessFinder | N/A | Ext. | Flow/No Flow | Variable. Demonstrated at 293 ft avg. | Yes | No | Yes | $2.71/ft | $0.48/ft |
| Internal Technologies | | | | | | | | | |
| Sahara® Video | >4 in. | Int. | >1 ft/s | Continuous | Yes | Yes | No | N/A* | N/A* |
| PipeDiver® | 24-60 in. | Int. | >0.7 to 1.5 ft/s | Pipe length | Yes | No | No | N/A* | N/A* |
| See Snake® | 2-16 in. and 20-28 in. (can be adapted to a custom diameter) | Int. | Dewatered; Flow version available. | Continuous | No | Yes | Yes | $15-$19/ft | $0.58/ft |
| External Technologies | | | | | | | | | |
| ECAT | >12-in. | Ext. | N/A | Every 1,200 ft | Yes | Yes | Yes | $3.60/ft | $0.94/ft |
| HSK | No diameter limit noted as advantage. | Ext. | N/A | Every 900 ft | No | Yes | Yes | $2.95/ft | $1.63/ft |
| CAP | No diameter limit noted as advantage. | Ext. | N/A | Every 300 ft | No | Yes | Yes | N/A* | N/A* |

* Cost data not provided by vendor due to developmental status of technology, etc.

**Technology Maturity**. The level of development differs substantially among the tools for the inspection of a 24-in. cement lined, cast iron pipe. For PipeDiver® and See Snake®, this demonstration was the first application of the technology for the inspection of a large diameter cast iron water main. Therefore, the demonstration helped to accelerate the testing and development of these emerging technologies under field conditions. For other technologies, this demonstration represented a very early application (e.g. Sahara® WTT and SmartBall™ PWA) and the data will provide a source of information to the vendors for improving tool performance with further calibration to excavation information from the field. Other technologies such as Echologics® ThicknessFinder have been deployed at multiple sites and therefore have more experience in calibrating inspection results to field conditions. All of the inspection vendors planned to use the demonstration to facilitate new technology developments and improvements. All of the technologies are still available as of the preparation of this report with improvements claimed since the time of the demonstration (see Appendix H and vendor websites listed in Section 2).

**Technology Implementation.** Some technologies were simple to implement with minimal modification to the water main and others required launching/retrieval of the tool. Water utilities can benefit from information on the ease of use of inspection tools and/or the complexity of site logistical and operational requirements. The access requirements, support equipment and number of personnel needed to deploy the inspection technologies varied substantially with each vendor. The demonstration provided information on the ability to mobilize, access the pipe, operate under given flow rates, and other site conditions for a 24-in., spun cast iron pipe with leadite bell and spigot joints, and a cement-lining. The logistical and operational information was summarized in detail in Table 2-1 for each technology. This included the number of technicians needed, any need for operator intervention, the number and spacing of pipe contact points, access requirements, and more. Other implementation factors of interest to water utilities are summarized in Table 2-5. For the internal inspection technologies, each vendor was capable of configuring their equipment to inspect the full 2,057 ft of pipe. For the external technologies, the scans of the exposed pipe were able to be completed.

Issues that were encountered for the acoustic pipe wall assessment technologies included signal interference from large air pockets and signal interference from the noise generated by the discharge at the end of the test pipe. However, these situations are unlikely to occur in a fully operational water main and are due primarily to the test pipe configuration.

For internal inspection technologies, both PipeDiver® and See Snake® provided inspection results for the entire pipe length used in the demonstration. For both vendors, this was the initial use of this technology implementation on an operational cast iron water main. At the time of the demonstration, See Snake® was a tethered prototype unit that was particularly intrusive, since it required the pipe to be dewatered and cut, and then the See Snake® was pulled through a dry line. The full-scale commercial system is now available to be launched in a live pipeline. There were some issues with control of the winch initially causing velocity excursions (e.g., jerking, and surging), but this was resolved. The demonstration of PipeDiver® showed that a large free swimming, in-line inspection tool could be launched and retrieved from an operating pipeline. Live insertion and retrieval of inspection tools within a water main is a key area for improvement and this demonstration assisted in acceleration of these efforts. No significant implementation issues were encountered except for a minor issue with launching of the PipeDiver®, which was overcome by modifying the tool so that it wouldn't get caught in a 4-in. gap in a joint downstream of the inspection point. As a result, the vendor recommends using Sahara® Video prior to the inspection to identify the exact layout of the insertion point.

No significant implementation issues were noted for the external technologies. Two of these technologies typically require excavation of 5 ft sections every 1,200 ft for ECAT and every 900 ft for RSG HSK. A keyhole excavation or pothole is used every 300 ft for RSG CAP. One excavation location used by AESL was near a large leak, which may have contributed to higher corrosion rates in that pipe section that may have biased the statistical model towards predicting larger defects. This highlights the importance of the selection of excavation locations to technology performance and the need for improvements in screening approaches for selecting locations that are representative of the remaining portion of unexposed pipe.

**Technology Inspection Results**. The pipeline condition data provided by each vendor varied from highly detailed defect location and sizing information to general pipe condition over larger areas of the test pipe. Ultimately, it is the decision of the water utilities to determine the level of analysis needed to make decisions regarding rehabilitation and replacement of a particular main. Familiarity with a variety of tools can be valuable to a utility, as well as having options that accommodate specific situations necessary to obtain a useful assessment of the pipe condition. Table 2-5 summarizes the format of the inspection results that can be expected from each technology (e.g., the inspection technology provides for general condition assessment information, identification of specific defects, and/or numerical results).

One conclusion drawn from this study is that the technologies tested would benefit from further calibration to a wider range of excavated pipe data from the field. While all of the exhumed pipes had metal loss, their condition with regard to overall metal loss was generally good. The average wall loss was calculated for all of the exhumed pipes and the greatest amount observed was 2.6%.

**Technology Costs.** Table 2-5 summarizes the estimated inspection costs and site preparation costs for the acoustic pipe wall surveys, internal inspection technologies, and external inspection technologies.

**Summary and Research Needs**. The inspection goal of each of the inspection technologies differed, as they attempted to balance maximizing inspection performance, while minimizing intrusion on the pipe and the direct cost of the inspection. The following conclusions can be drawn regarding further research and technology development needs and improved methodologies for evaluating pipe wall condition inspection technologies as discussed below.

The technologies tested would benefit from further calibration with field data to improve their accuracy and reduce the amount of overcalls (e.g. prediction of pipe in worse condition than its actual condition). The data from this field demonstration was provided to the vendors and will aid the developers in improving their calibration to excavation results.

Although the acoustic pipe wall screening technology demonstration data suggests that several interesting variations exist in the pulse velocity at different points along the pipeline, it was unclear whether the data revealed actual changes in the hoop stiffness of the pipe wall, or if the data had been affected by the presence or condition of the mortar lining or other pipe stiffness enhancements (such as previous repairs on the pipe). Improved capability to identify the causes of these acoustic velocity changes would be useful. Good construction and maintenance records may be a critical source of useful data.

The test pipe at LWC was being replaced for capacity issues and overall the pipe appeared to be in good condition (defined as average wall loss less than 4% and no detected through-wall defects) both from a visual assessment of the pipe as it was excavated and based upon the 12 exhumed pipes that were selected for further manual and/or laser assessment. A future field demonstration where the test pipe had a larger variation in condition along its length, including larger defects and more significant wall loss would provide for an improved understanding of the detection capabilities of the inspection technologies.

Each technology provides different types of inspection results at widely varying resolutions. For water utilities, this can make a one-to-one comparison of the technologies and inspection results difficult to achieve. Vendors may provide an evaluation that does not yield quantitative, numerical data (e.g., wall thickness) along the full length of the pipe. Instead, a qualitative pipe condition may be provided, the basis of which is not well defined and/or proprietary to the vendor.

Because of the inherent uncertainty in the condition of an operational water main (prior to a demonstration), there is a need to simulate key pipe scenarios under controlled conditions to further test inspection technologies and their ability to accurately characterize pipe condition. The size of the machined defects in this study ranged from 1- to 6-in. in length and 20% to 70% wall loss. Many of the external inspection methods averaged over large areas and there was not sufficient granularity to directly compare the scans with the actual dimensions of the machined defects. Future controlled condition testing in a test bed could be conducted with a larger range of calibration and test defect sizes (while minimizing any stress on the pipe that could cause local changes to its magnetic properties).

# 3.0: MATERIALS AND METHODS FOR FIELD DEMONSTRATION

## 3.1 Site Description

**3.1.1 Site Location**. Louisville is located in the north-central portion of Kentucky, immediately south of Indiana along the Ohio River. Its climate can be described as humid sub-tropical with yearly temperatures ranging from 0°C in January to 25°C in July. The city's estimated population, as of 2006, was just fewer than 600,000; the Louisville Metropolitan Area's population was approximately 1,250,000. Supplied by the Ohio River, the source water is treated and transmitted to service taps by LWC, which was granted a charter from the Kentucky Legislature in 1854. Under this charter, water was first provided to the citizens of Louisville by LWC in 1860. Currently, LWC treats and transmits 135 MGD of water to 270,000 service taps through 3,500 miles of water mains, ranging in diameter from 1 to 60-in. Under its MRRP, the company replaces over 35 miles of pipe every year as either a preventive or reactionary effort to maintain the water transmission and distribution system.

As part of LWC's pipe replacement and rehabilitation program, a 2,500-ft length of 24-in. diameter pipe that was scheduled for replacement was made available for the demonstrations of inspection and condition assessment technologies. A continuous 2,057-ft section of this pipe was used for the demonstrations. The pipeline right-of-way is in the north lane of Westport Road, from the intersection of Westport Road and Chenoweth Lane, to the intersection of Ridgeway Avenue and Westport Road (see Figure 3-1). At Ridgeway Avenue, the 24-in. diameter line goes under a set of CSX railroad tracks.

**3.1.2 Test Pipe Condition.** The portion of the 24-in. diameter transmission main along Westport Road between Chenoweth Lane and Ridgeway Avenue was made available for the field demonstration project (referred to herein as "the test pipe"). The test pipe is Class 150 deLavaud spun cast iron that is lined with a factory-installed cement mortar and represents approximately 2,500 ft of transmission line. The test pipe was installed in September 1933 and had a burial depth between 3.5 and 6.0 ft. Wall thicknesses of the pipe range from 0.68 to 0.73-in., as measured periodically during routine maintenance and inspections or during repairs. During a site visit in May 2009, wall thicknesses of pipe samples removed during the installation of a 24-in. by 12-in. tee were measured and ranged from 0.76 to 0.78-in. The test pipe typically operates at pressures between 45 and 50 pounds per square inch (psi), while transmitting 4 to 6 MGD of flow. Table 3-1 summarizes the historical, operational, and environmental characteristics of the test pipe.

In preparation for the new installation and prior to the demonstration, all taps and off takes on the 24-in. diameter test pipe were moved to a 12 in. diameter parallel service line. The test pipe was bypassed and taken offline, but could be filled or drained as needed for each demonstration. During the demonstration, traffic was restricted to a single lane and traffic flow was sporadic. The amount of traffic during the demonstration was not separately measured or recorded.

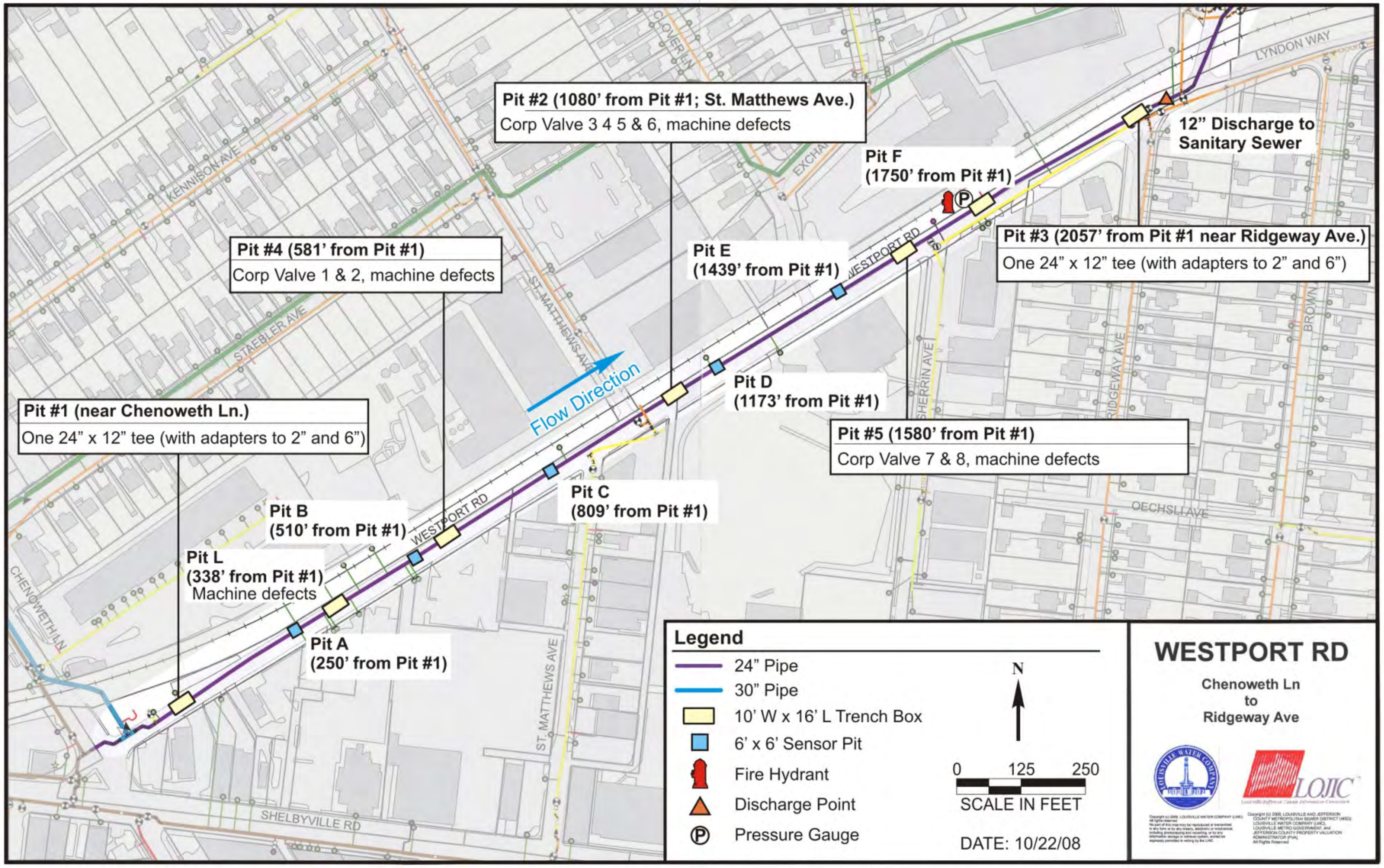


Figure 3-1. Location Map of Westport Road Transmission Main Replacement Project

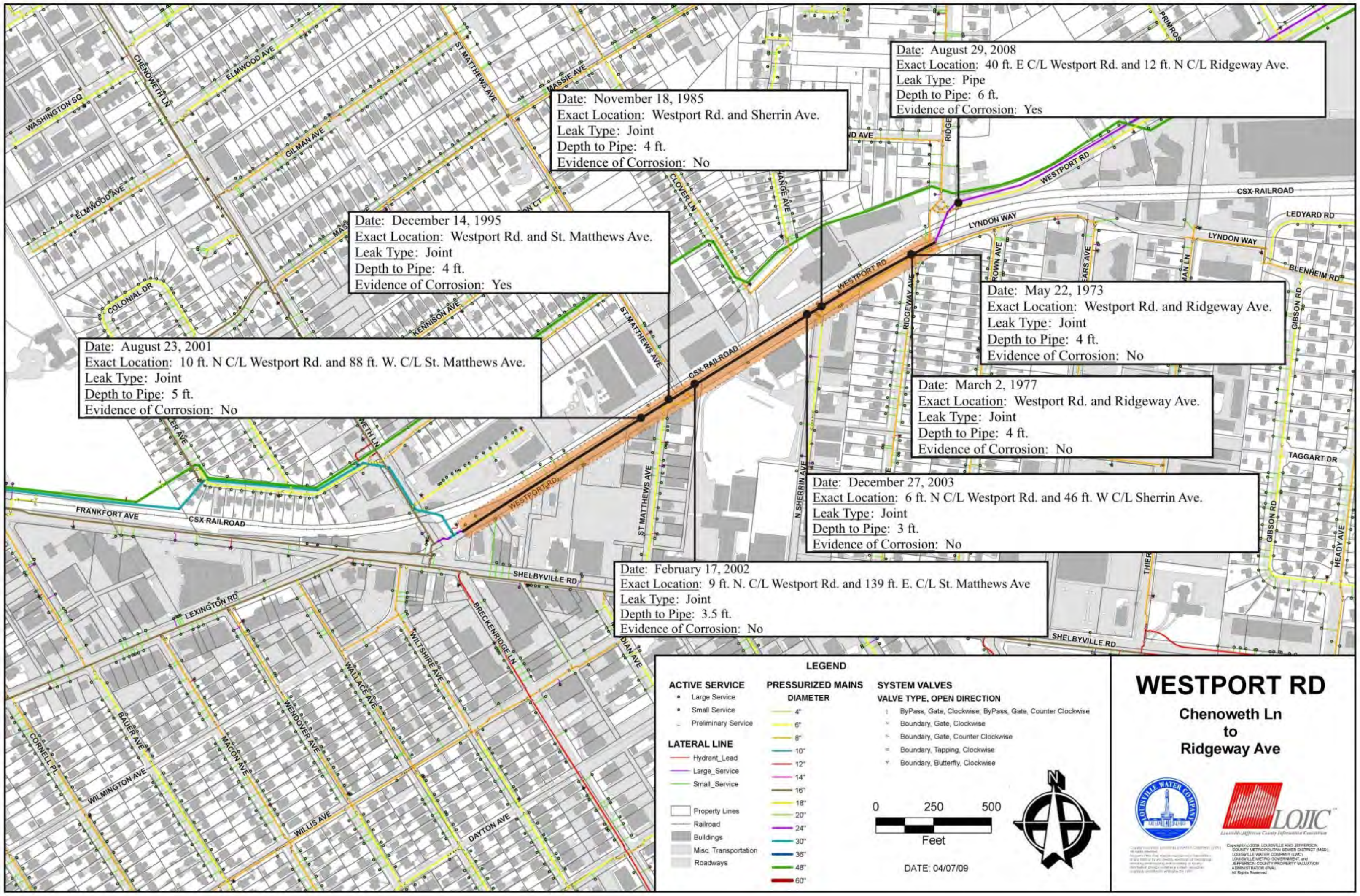
**Table 3-1. Summary of Historical, Operational, and Environmental Characteristics of Test Pipe**

| ***Historical*** | |
|---|---|
| Pipe Material | Cast iron |
| Installation Date | 09/1933 |
| Pipe Segment Length (ft) | 12 |
| Pipe Inner Diameter (in.) | 24 |
| Pipe Class | deLavaud Spun Cast; Cement lined; Class 150 |
| Pipe Thickness (in.) | 0.68 – 0.78 |
| Approximate Total Pipe Length (ft) | 2,000 |
| Burial Depth (ft) | 3.5 – 6.0 |
| Pipe Lining | Factory Applied Cement Mortar |
| Pipe Lining Thickness (in.) | Variable, on the order of 0.25 |
| External Coating | Bitumen paint |
| Type of Joints | Leadite |
| Land Use over Main | Residential traffic; bituminous paving |
| Leak History (recorded) | Eight leaks since 1973 (see Figure 3-2) |
| Date of First Joint Leak (recorded) | 05/22/1973 |
| Date of First Pipe Break (recorded) | 08/29/2008 (not within 2,057-ft test pipe) |
| ***Operational*** | |
| Typical Operating Flow (MGD) | 4 – 6<br>• Flow throttled due to concerns of main breaks<br>• Available flow for inspection ranging from 1,400 to 2,800 gpm (or 1 to 2 ft/sec) due to sewer restrictions |
| Typical Operating Pressure (psi) | 45 – 50 |
| Water pH (S.U.) | 8.2 |
| ***Environmental*** | |
| Soil Parameters (moisture, pH, resistivity, redox potential, etc.) | No historical data[a] |
| Average Monthly Temperature (°C) | January through December: 0, 2, 8, 14, 19, 23, 25, 24, 21, 14, 8, 3<br>Minimum – 0 (January)<br>Maximum – 25 (July) |

(a) Soil characterization was performed during the demonstration project.

**3.1.3 Leak History.** Seven joint leaks and one pipe break have been reported along the test pipe from May 1973 to August 2008; however, no information exists regarding the test pipe leak history prior to 1973. Figure 3-2 shows the location and date of the recorded leaks and breaks: two near the intersection of Ridgeway Avenue and Westport Road on May 22, 1973 and March 2, 1977; three near the intersection of St. Matthews Avenue and Westport Road on December 14, 1995, August 23, 2001, and February 17, 2002; and two near the intersection of Sherrin Avenue and Westport Road on November 18, 1985 and December 27, 2003. All of the seven joint leaks occurred at leadite joints.

Since no evidence of wall loss was noted at the time of the repairs, most of these joint leaks are assumed to have been induced by settling/consolidation of underlying fill material or natural soils or as a result of the freeze/thaw cycle causing differential movement of pipe segments attached to the common joint. The exception to this was the December 14, 1995 joint leak at the intersection of St. Matthews Avenue and Westport Road in which evidence of corrosion was observed.



Date: August 29, 2008
Exact Location: 40 ft. E C/L Westport Rd. and 12 ft. N C/L Ridgeway Ave.
Leak Type: Pipe
Depth to Pipe: 6 ft.
Evidence of Corrosion: Yes

Date: November 18, 1985
Exact Location: Westport Rd. and Sherrin Ave.
Leak Type: Joint
Depth to Pipe: 4 ft.
Evidence of Corrosion: No

Date: December 14, 1995
Exact Location: Westport Rd. and St. Matthews Ave.
Leak Type: Joint
Depth to Pipe: 4 ft.
Evidence of Corrosion: Yes

Date: May 22, 1973
Exact Location: Westport Rd. and Ridgeway Ave.
Leak Type: Joint
Depth to Pipe: 4 ft.
Evidence of Corrosion: No

Date: August 23, 2001
Exact Location: 10 ft. N C/L Westport Rd. and 88 ft. W. C/L St. Matthews Ave.
Leak Type: Joint
Depth to Pipe: 5 ft.
Evidence of Corrosion: No

Date: March 2, 1977
Exact Location: Westport Rd. and Ridgeway Ave.
Leak Type: Joint
Depth to Pipe: 4 ft.
Evidence of Corrosion: No

Date: December 27, 2003
Exact Location: 6 ft. N C/L Westport Rd. and 46 ft. W C/L Sherrin Ave.
Leak Type: Joint
Depth to Pipe: 3 ft.
Evidence of Corrosion: No

Date: February 17, 2002
Exact Location: 9 ft. N. C/L Westport Rd. and 139 ft. E. C/L St. Matthews Ave
Leak Type: Joint
Depth to Pipe: 3.5 ft.
Evidence of Corrosion: No

Figure 3-2. Locations and Details of Pipe and Joint Breaks and Leaks

The only recorded pipe break occurred on August 29, 2008, approximately 12 ft north of the centerline of Ridgeway Avenue and 40 ft east of the centerline of Westport Road. The break appears to have occurred near a joint and propagated longitudinally along the pipe (see Figure 3-3), resulting in complete failure. The pipe break was caused by an attempt to operate the line at its full capacity, which indicated that the pipe might have lost part of its original structural integrity due to aging. It should be noted that the location of the pipe break is outside the test area (that is, not strictly part of the test pipe). However, it is noteworthy because of the nature of the break and because it occurred just a few days before the EPA Forum, which prompted LWC to offer the pipe for this demonstration.

Note arrow pointing to longitudinal propagation of crack

**Figure 3-3. Pipe Break along Westport Road Adjacent to Test Area in August 2008**

### 3.2 Technology/Vendor Selection

The TO 62 State of the Technology Review (SOTR) report (Thomson and Wang, 2009) provides an overview of the state of inspection technologies for ferrous pipes. The technologies selected for demonstration at Louisville, KY were based on the TO 62 SOTR report, feedback from the Technology Forum, and an additional literature search on relevant reports prepared by organizations such as Water Research Foundation (formerly American Water Works Association Research Foundation), Water Environment Research Foundation (WERF), and EPA, as well as vendors' Web sites. A list of potential candidate technologies was compiled, which included acoustic-, magnetic-, electromagnetic-, and ultrasonic-based technologies. Technologies that require the removal of coatings and preparation of the pipe surface (such as ultrasonic tools for wall thickness measurement) are well established and were not considered in this field demonstration. Innovative and emerging ultrasonic tools can be demonstrated offsite after the pipe is exhumed.

The candidate technologies were further screened based on (1) suitability of the technologies for the test pipe diameter and material, (2) readiness of the technologies within the field demonstration timeline, and (3) potential to yield useful data for interested utilities. It is also important that the technologies considered not only represent those that are commercially available, but also those that are in the stage of development that could be demonstrated in the field. An added benefit of this demonstration project is to bring new technologies to the forefront of condition assessment research and allow utilities to become familiar with these technologies.

After the technology screening, an e-mail transmittal was sent to prospective vendors in February 2009 to solicit expression of interest. Most vendors responded promptly and expressed their keen interest in participating in the demonstration. Several vendors were eliminated from further consideration due to either lack of interest or financial constraints. Six vendors agreed to participate in and provide partial in-kind contributions to the field demonstration project.

## 3.3 Technology Description

**3.3.1 Acoustic Pipe Wall Assessment Technology Description.** Relatively new, non-destructive technologies are available for providing the estimates of the wall thickness averaged over an interval that does not require taking pipes out of service. These methods typically work by inducing an acoustic signal in pipes either by releasing water at a hydrant or inducing vibrations in the pipe wall (e.g. tapping, electro-mechanical shaker, acoustic pulses, etc.) and measuring how quickly acoustic waves travel along a section of pipe. The acoustic signals are measured either by external sensors positioned at locations along the pipe such as at fire hydrants, control valves, and/or excavated holes or by internal sensors such as hydrophones. The velocity of the acoustic vibration is then calculated based on the sensor spacing and time delay between the measured acoustic signals. Average wall thickness of the pipe section is then estimated based on its relationship to the acoustic velocity and the hoop stiffness of the pipe.

Systems can be fully external or used for a combination of internal and external components. For entirely external systems, the length of the pipe section over which the acoustic velocity is measured is chosen based on the local water main configurations, but usually ranges from about 300 to 700 ft between sensors. If a higher thickness resolution is needed, the acoustic sensors can be moved closer together by using keyhole vacuum excavations to access the pipe or by inserting arrays of closely spaced sensors. In the case of wall thickness assessment systems with internal components, data can be collected by positioning the movable sensor at specific distance intervals or by continuously collecting data over the length of the pipeline.

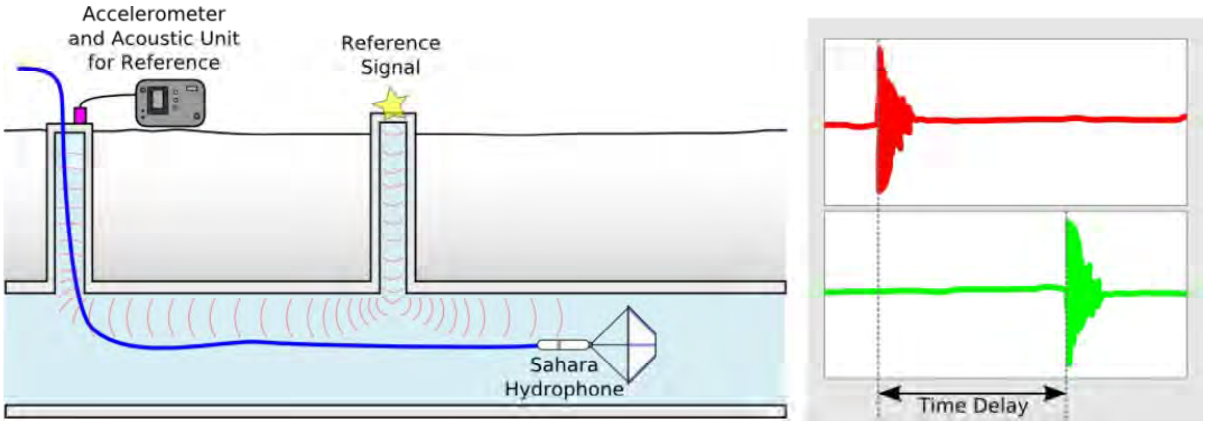
The pipe wall thickness determined by these methods represents an average value for the pipe section over which acoustic velocity is measured. In the development of this technology, research has shown pipes will have a more-or-less uniform thickness profile over significant lengths (~150 ft to 300 ft) as soil and bedding conditions are unlikely to change significantly over such distances (Hunaidi et al, 2004) . Also, the average general wall thickness is believed by some to be a better indicator of the general structural condition and remaining life of pipes than the depth of individual corrosion pits, especially for the purpose of long-term planning of rehabilitation and replacement needs (Hunaidi, 2006).

The following average wall thickness assessment technologies participated in the demonstration at LWC:

**Sahara® Wall Thickness Testing.** The Sahara® WTT system, provided by PPIC (now part of Pure), is a non-destructive inspection technology that estimates the average pipe wall thickness over a range of pipe segments in large diameter water transmission mains. Sahara® WTT can be performed in conjunction with a Sahara® Leak Detection inspection under the same operating pressure, flow velocity, and inspection distance constraints (pressure range from 7 to 230 psi; flow range from 1 to 5 ft/s; survey length ~6,000 ft depending on pipeline geometry, flow conditions, and internal pipe conditions).

Operation of the Sahara® WTT system is similar to the Sahara® Leak Detection system in which a 1 in. diameter hydrophone is inserted into a live pipeline through any standard tap that is 2 in. in diameter or greater. A drogue (parachute) is attached in front of the hydrophone to capture water flow and carry the sensor and cable down the pipeline. However, wall thickness testing requires installation of a secondary acoustic sensor (either an external accelerometer attached to the pipe surface or an additional internal hydrophone) and generation of reference signals (e.g., test strikes at access points or sounds produced by a speaker) within the pipe to facilitate testing as shown in Figures 3-4 and 3-5.

The sound waves generated by the reference signal propagate through the pipeline; the propagation speed is affected by the condition of the pipe wall over the interval. Pairs of acoustic sensors separated by a known distance are used to estimate the time that the reference signal arrives. This information is used to calculate the speed of sound within the pipe and thus the average wall thickness over the specific intervals. Detailed pipe information and fluid parameters are needed to calculate the average wall thickness. Current testing procedures require access to the pipe (i.e. hydrant, flange, or exposed pipe surface) a minimum of every 400 ft to generate reference acoustic signals.



(Courtesy of vendor)

**Figure 3-4. Sahara Wall Thickness Technology**

(Courtesy of vendor)

**Figure 3-5. Accelerometer Acoustic Sensor Attached to the Sahara® Insertion Tube**

The tethered control of the Sahara® system allows the hydrophone to stop at precise locations for each interval. Since the wall thickness average intervals are defined by hydrophone location, a high resolution can be attained by indexing the hydrophone a short distance and repeating the data acquisition. However incrementing the hydrophone in fine intervals will take increased time and hence costs. For these tests, the travel times for sound pulses were determined at 33-ft intervals, and then the sound velocity was calculated for the same interval.

Sahara® WTT has the same inspection limitations as the leak detection system. Like the leak detection system, air pockets can significantly interfere with the wall thickness measurements by affecting the acoustic signal propagation. Some factors affecting average wall thickness accuracy include: length of a given section over which acoustic velocity is measured (the shorter, the more uncertain); distance readings of the sections; accuracy of the pipeline and fluid parameters; unknown pipe features and rehabilitation; large stationary air pockets; and, background noise. Each deployment at a site includes: calibration of Sahara® WTT sensor's sensitivity and distance reading; calibration of reference acoustic sensor for synchronization with Sahara® WTT; and, repeatability tests. A relative result is obtained based on all calculated results in every 33 ft interval. A baseline pipe wall thickness would be calculated from a group of intervals that show similar wall thickness results (< 2% difference from the mean), and the result of other portions would show the wall thickness change ratio to this baseline value. This relative result is provided instead of a calculated wall thickness to account for possible uncertainties introduced by composite pipe material and fluid parameters.

**SmartBall™ Pipe Wall Assessment (PWA).** SmartBall™ (PWA) uses acoustic technology to assess general pipeline condition. SmartBall™ (PWA) system is the SmartBall™ Leak and Gas Pocket Location tool (Nestleroth, 2012) plus the additional capability of determining pipe wall stiffness. The SmartBall™ (PWA) system components include: (1) the SmartBall™ , which travels through the full pipe; (2) insertion and extraction devices for the SmartBall™; (3) SmartBall™ Receivers (SBR) that are placed at fixed locations along the pipeline to receive acoustic pulses from the SmartBall™ that are used to help track its position vs. time; and, (4) pulsers. also positioned along the pipeline, that send into the pipeline low frequency acoustic pulses whose velocity varies with, and can be correlated to, the local hoop strength of the pipe.

The SmartBall™ contains an acoustic acquisition device for leak sounds, etc.; an acoustic pulse generator for transmitting acoustic signals to the SBRs for determining SmartBall™ location; accelerometers and magnetomers, also for determining SmartBall™ location; timing devices for documenting time of transmission and reception of acoustic signals, and for synchronization with SBR and pulser data; data storage, and power supply. The SmartBall™ instrumentation is housed within an aluminum case, which is coated with an elastomer. It is then placed within a foam ball (see Figure 3-6) prior to inserting into the pipeline. SmartBall™ is free swimming, does not require dewatering of the line or pipe excavation, and can be operated for up to 15 hr. It is applicable for pipe diameters greater than 10-in., but is most effective in pipes greater than 24-in. in diameter. The size of the SmartBall™ selected depends on the various characteristics of the pipe, including diameter, valves, and appurtenances available, but is usually less than one third of the diameter of the pipe.

SmartBall™ is inserted into the pipeline through a 4-in. diameter tap with a gate valve using an insertion tube bolted to the valve (see Figure 3-7); this type of connection generally must be added to a water main. As SmartBall™ is rolled through the pipe by the water flow, the PWA technology records information for determining the pipe hoop stress at short, consecutive intervals along the pipe, and stores this information for later analysis. SmartBall™ is then retrieved through another 4- or 6-in. diameter gate valve using an extraction tube bolted to the valve that contains a specialized net that compresses the foam to capture and remove it from the pipeline. Information can then be obtained from the SmartBall™ by downloading the data at the end of the survey. The SmartBall™ software provides the acoustic information relative to the distance the ball travelled.

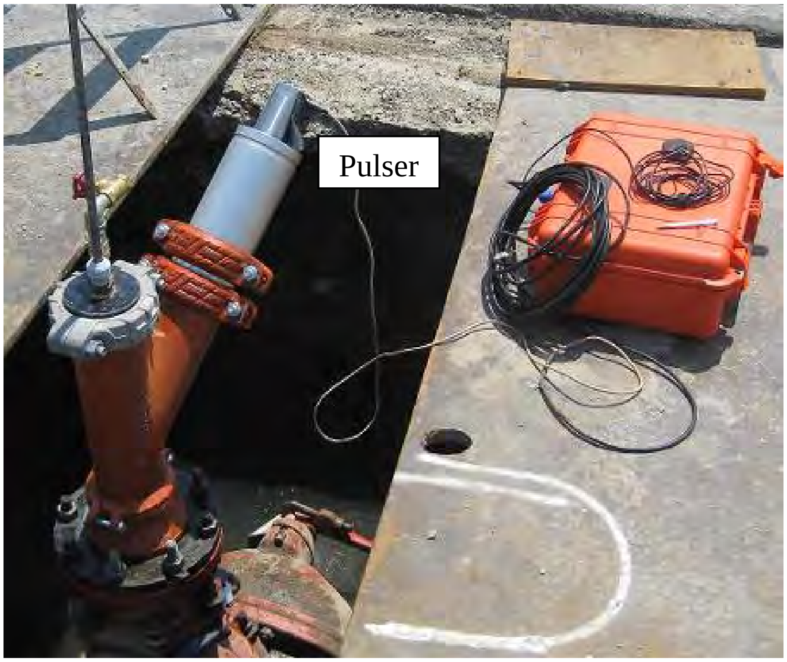
The SmartBall™ PWA technology uses low frequency acoustic pulses to evaluate the hoop stiffness of the pipe wall. The propagation velocity of a transmitted low frequency pulse from the pulser through a pulsePWA technology utilizes the SmartBall™ acoustic sensor and long range mobility and tracking capabilities to simultaneously assess the pipe wall condition and detect leaks.

The SmartBall™ PWA technology uses low frequency acoustic pulses to evaluate the hoop stiffness of the pipe wall, which is indicative of pipe wall condition. The pipe wall condition is assessed by effectively measuring the propagation velocity of a transmitted low frequency pulse from the pulser, and then determining the hoop stress of the pipe. PWA technology utilizes the SmartBall™ acoustic sensor and long range capabilities to simultaneously assess the pipe wall condition and detect leaks.

The low frequency pulses are generated by pulsers mounted onto the insertion and extraction stack (see Figure 3-8). Pulsers can also be mounted on typical fittings found on pipes, such as valves and can also be strapped onto the pipe itself. The number of pulsers used is dependent on the length of pipe inspected. For this field demonstration of a fairly straight, approximately 2,057 ft long pipeline, three pulsers were required. The propagation velocity is measured based on the arrival time of the acoustic wave from the upstream and/or downstream pulsers and is compared to the arrival time difference of the pulse(s) acquired at the previous position. The pipe wall stiffness in the interval traversed by the SmartBall™ between the pulses is correlated based on the propagation velocity of the pulse. As the pipe wall stiffness decreases and increases, the propagating velocity decreases or increases respectively.

Figure 3-6. Aluminum Case and Foam Housing for SmartBall™ Acoustic Acquisition Device, Data Storage, and Power Supply

Figure 3-7. SmartBall™ Insertion and Extraction Tubes



(Courtesy of Pure)

**Figure 3-8. SmartBall™ PWA Insertion Stack with Pulser**

The low frequency pulse generated by the pulser can be obscured by loud noise sources nearby and by bends and elbows in the pipe. To compensate for the attenuation, three pulsers at nominally 1,000 ft spacing were used for the field demonstration to ensure that the SmartBall™ would detect at least one pulse at any given time in the straight pipe. Furthermore, the sensitivity and resolution of the SmartBall™ PWA technology is also dependent on the velocity of the SmartBall™. The typical spatial resolution of the SmartBall™ PWA tool is at least one data point every two ft. Since the pipe wall stiffness is assessed at 2 ft intervals, it is unlikely that individual pits will be detected. However, the tool is stated to have the capability to highlight areas where a cluster of pits compromises hoop stiffness or where there is a local thinning of the pipe wall.

**ThicknessFinder.** ThicknessFinder uses a similar detection methodology as LeakFinderRT; however, instead of listening for leaks, an acoustic signal is induced in the pipe to determine the acoustic wave velocity in a section of pipe. For a given distance between the sensors, the acoustic wave velocity can be calculated by $v = d/t$, where d is the distance between the sensors, and t is the time taken for the acoustical signal to propagate between the two sensors. If an accurate measurement of the acoustic wave velocity is made, it is possible to back-calculate the remaining average thickness of the pipe between the two sensors. Typically, the length of the pipe section over which the acoustic velocity is measured is 300 ft to 1,000 ft; however this distance can be decreased to anywhere between 100 ft to 300 ft to increase the resolution.

Echologics proprietary leak noise correlator, LeakfinderRT, was used to determine the acoustic velocity. An acoustic source outside the section of pipe spanned by the surface mounted sensors (an ‘out-of-bracket’ source) was used to induce an acoustic wave in the pipe; the time delay difference was measured at the sensors; and, the acoustic velocity was calculated from the sensor separation and time delay data. At each site, the noise source to induce the acoustic wave was either operation of a fire hydrant or impacting a valve or hydrant.

The vendor states that the average wall thickness of the pipe section between the acoustic sensors is then back-calculated from a theoretical model. As the pipe wall thickness decreases over time, the acoustical wave velocity decreases. The acoustical wave velocity is given in the Wave Velocity Thickness Model below, which is based on research from NRCC (Hunaidi, 2004). This model does not include secondary factors that affect the propagation velocity such as water temperature and pipe wall inertia. These factors are not shown here, but were accounted for in the final results.

$$v = v_o \sqrt{\frac{1}{[1 + (D/e)(K_{water}/E_{pipe})]}}$$

where

$v$: Propagation velocity of leak noise in pipe
$v_o$: Propagation velocity of sound in an infinite body of water
$D$: Internal diameter of pipe
$e$: Thickness of pipe wall
$K_{water}$: Bulk modulus of elasticity of water
$E_{pipe}$: Young's modulus of elasticity of pipe material

Wave Velocity – Thickness Model

The acoustic propagation wave (the water hammer mode) propagates as a compression wave in the fluid, and a dilatational wave in the pipe. There are two key implications of waves traveling in the fluid and pipe:

1. Only the structural part of the pipe that can carry load will contribute to the structural stiffness of the pipe, therefore deposits on the pipe wall such as tuberculation or graphite will not be included in the average wall thickness measurement.
2. The minimum structural thickness of the pipe is measured, as the level of strain of the pipe will be dependent on the minimum wall thickness at any point around the circumference of the pipe.

Using the above equation, the pipe wall thickness calculated from these measurements represents an average value for the pipe section over which the acoustic velocity is measured. The technology has been applied to generally much greater sample lengths of pipe than could be done with random sampling. Therefore, when surveying long lengths of pipe, the operators begin to look for anomalies in the measurements that could indicate degraded sections of pipe. When these are seen, the vendor suggests the distance between the sensors may be decreased and more resolution obtained. Generally, pipes will have a fairly uniform thickness profile with isolated pockets of corrosion over significant lengths (e.g., 150 to 300 ft) as soil and bedding conditions are unlikely to change significantly over such distances. Also, average wall thickness values are suitable to evaluate the residual life of pipes for the purpose of long-term planning of rehabilitation and replacement needs. The use of techniques such as evaluation of stray currents, soil corrosivity studies, and main break history may be used in conjunction with this average wall thickness data to evaluate overall pipe condition.

**3.3.2 Internal Inspection Technology Description.** Inline inspection technologies have been used for years in the oil and gas industry to inspect pipelines for structural integrity issues such as corrosion and mechanical damage. Inline inspection technologies for water mains can range from relatively simple CCTV visual tools that assess the ID of the pipe to complex tools that assess the pipe wall thickness including MFL, ultrasonic, and RFEC (RFT) tools. The more complex technologies have only recently been used by utilities for inspection of large water mains after a few main breaks that resulted in extensive service disruptions, significant property damage, and costly repairs. Inline inspection systems that provide valuable pipeline condition information for critical, non-redundant, in-service water mains are particularly desirable,

Issues that must be overcome for a wide-spread use of inline inspection technologies (other than CCTV) for water mains includes the lack of launching and receiving facilities on existing water mains, the variety of materials used to construct water pipelines, and the expense of conducting such inspections.

Three inline inspection technologies participated in the demonstration at LWC: **Sahara® Video, PipeDiver®,** and **See Snake®** . Each technology is described in more detail below.

**Sahara® Video.** Sahara® Video provides real-time, in-service CCTV inline inspection of water mains. During the inspection, the internal condition of the pipe is generally assessed and pipeline features such as cement liner condition, valve locations, and debris or blockages are documented.

The Sahara® Video system utilizes the same control system and tethered cable as the Sahara® Leak Detection system, but the hydrophone sensor head is switched to a video camera head that traverses the pipeline after being inserted through a standard 2 in. tap. Additionally, the drogue (parachute) is attached just behind the camera rather than in the front to carry the camera and cable down the pipeline without obstructing the camera's view (see Figure 3-9).

An operator stands by at the controller station to control camera deployment and views the video output in real-time. A second operator traverses the pipeline above ground using a tool to detect the exact location of the camera as it travels through the pipe. When an item of interest is seen the second operator will make a mark on the ground to identify the location and record a global positioning system (GPS) point for reference.

Like the Sahara® Leak Detection system, the Sahara® video system has a limited survey length based on the pipeline configuration and available flow rate. One circumstance or factor affecting accuracy is video clarity. Video images become less clear in larger diameter pipes due to diffuse lighting, reduced field of view, and unclear water. To calibrate the video system, each video camera is tested and compared to a standard frequency response. Video is interpreted and analyzed in real-time, but also recorded for future examination.

**Figure 3-9. Sahara® Video System**

**PipeDiver®.** PipeDiver® is a non-tethered, free swimming platform for inspection of in-service water mains (see Figure 3-10). The inspection vehicle allows inspection of pipelines from 24-in. in diameter and larger through two 12-in. diameter taps installed on the pipeline, one at each end of the inspection region. Large insertion and extraction tubes are installed on the 12-in. taps for launching and receiving the tool (see Figure 3-10). Alternatively, reservoirs or open channels can be used as insertion and extraction points.

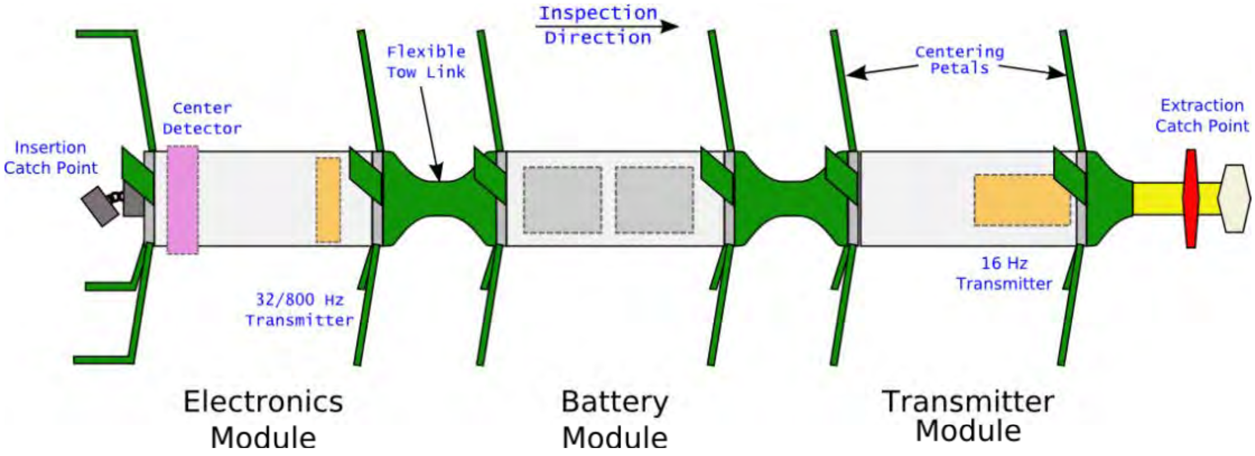
PipeDiver® is a modular system that includes an electronics module, battery module, and transmitter module for above ground tracking. PipeDiver® uses RFEC technology to generate magnetic currents in ferrous pipes for detection of pipe anomalies. Pipe anomalies change the uniformity of the magnetic current and this change can be measured with sensors. The vendor claims PipeDiver® was designed to estimate the location, size, and depth of major corrosion anomalies in the pipe wall. A schematic of the PipeDiver® inspection vehicle is provided in Figure 3-11.

For a standard launch, the insertion tube containing the PipeDiver® vehicle is attached to the 12-in. tap before being filled with water, pressure equalized, and opened to the pipeline. The internal insertion piston pushes the PipeDiver® vehicle into the pipe and, once fully in the pipe, the vehicle is released and begins to travel with the flow (see Figure 3-12). For a standard retrieval, once the PipeDiver® vehicle reaches the extraction side, a robotic claw and net which blocks the entire pipe diameter grabs the front of the vehicle and secures it before pulling up out of the pipe and into the retrieval tube (see Figure 3-13).

The PipeDiver® vehicle travels at approximately 90% of the pipeline's flow rate, the neutrally buoyant inspection vehicle can run for up to 30 hr in a single insertion. Flexible fins are used to center the tool within the pipe and provide propulsion. Its flexible design also allows PipeDiver® to navigate through most butterfly valves and bends in the pipeline, while travelling long distances.

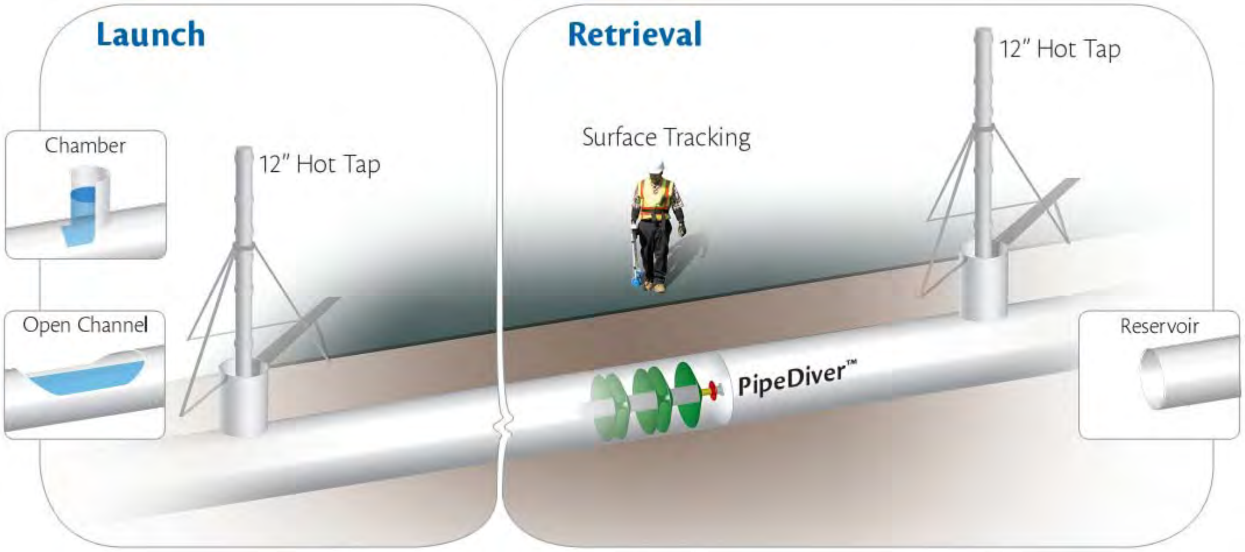
RFEC works on the basic theory that when a time harmonic magnetic field is generated inside a metallic pipe it has two paths from the exciter to detector coils (see Figure 3-14). The direct path remains inside the pipe and couples the coils directly, while the remote path remains outside of the pipe as long as possible. When the exciter-detector coil separation exceeds 1.5 pipe diameters, the signal from the remote field significantly dominates the total signal received at the detector. Since the remote field path passes twice through the pipe wall, any variation in magnetic wall properties including wall thickness, conductivity, and magnetic permeability will result in a change in the detector signal. During the demonstration of this developmental system, exciter coil position, frequency and type, along with sensor configuration and type were changed and the results combined. Note that the changes in signals appear twice in an RFEC tool, when the exciter and the detector pass respectively; the data analysis procedures must match pairs of signals in order to properly locate corrosion defects.

**Figure 3-10. PipeDiver® Inspection Vehicle (left) and Insertion Tube (right)**



(Courtesy of vendor)

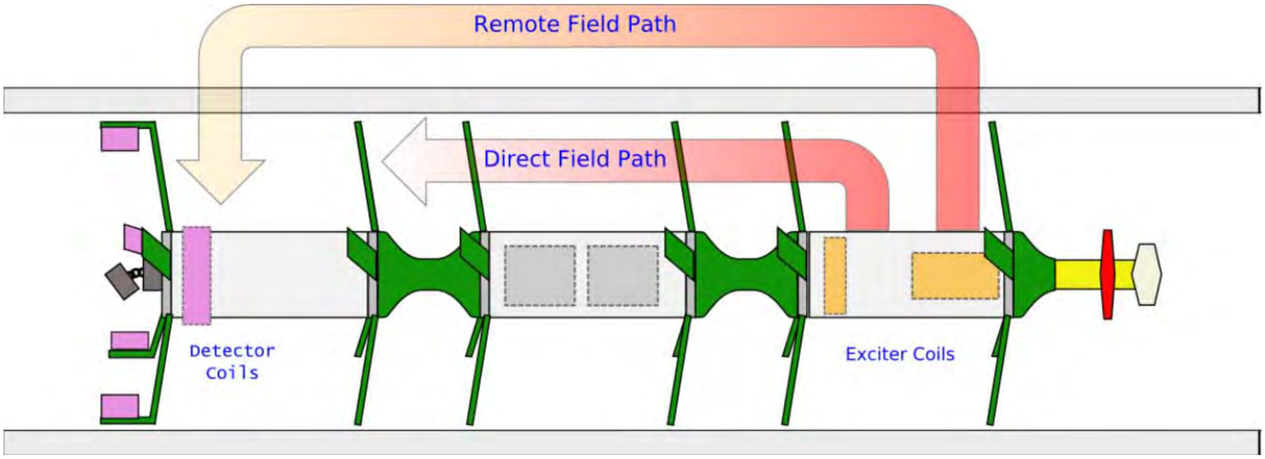
**Figure 3-11. Schematic of PipeDiver® Inspection Vehicle**



(Courtesy of vendor)

**Figure 3-12. The PipeDiver® Inspection System**

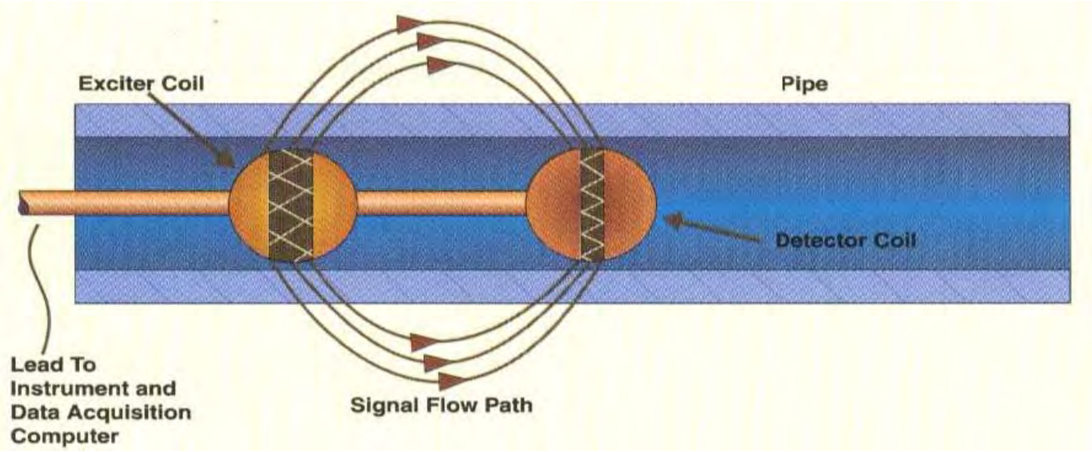
**Figure 3-13. PipeDiver® Extraction Tube and Robotic Claw**



(Courtesy of vendor)

**Figure 3-14. RFEC Signal Paths**

**See Snake®.** Russell NDE Systems Inc. custom developed a 24-in. See Snake® remote field testing (RFT) tool specifically for the field demonstration. The See Snake® technology employs remote field technology for measuring pipe wall thickness. RFT works by detecting changes in an alternating current (AC) electromagnetic field generated by the See Snake®. As the electromagnetic field interacts with the metallic pipe wall, it increases in magnitude at locations where metal loss exists. These changes in the electromagnetic field can be detected and measured with on-board detectors and processed using analog-to-digital (A/D) converters and digital signal processors (DSPs). The data is stored on-board for analysis upon completion of the inspection run and also sent down the wire line for real-time examination. Dedicated software is used to generate data on pipeline wall thickness and the location of metal loss. Figure 3-15 schematically shows the magnetic coupling path between the exciter section of the tool and the detectors.



(Courtesy of Russell NDE Systems Inc.)

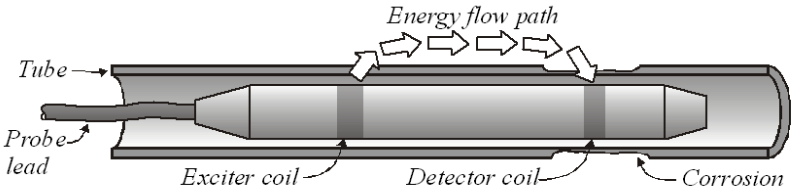
**Figure 3-15. Schematic of Magnetic Interaction between RFT Tool and Pipe**

The tool is usually a few inches smaller than the pipe diameter and requires about 0.25- to 1-in. clearance around the tool. The hard diameter of the tool is significantly smaller than the ID of the pipe to allow for passage around protrusions, lining, and scale within the pipe. Centralizers maintain a uniform annulus between the tool and the pipe. The recorded RFT signal is sent in real-time to a laptop via a wire line, which runs over an odometer sheave to provide an accurate distance reading for the tool. The RFT tool detects wall thinning caused by corrosion or erosion, as well as line features such as bell and spigot joints, couplings, branches and elbows. The amount of wire line on the winch limits the range of tethered runs, and battery power would limit the range for future free-swimming configurations. Ultimately, the See Snake® is designed to be launched in a live pipeline; however this was not possible for the demonstration because it was a prototype system. A photo of the third of three modules of the See Snake® is shown in Figure 3-16. The vendor limited photography of the proprietary, prototype unit.

In the basic RFT probe shown in Figure 3-17, there is one exciter coil and one detector coil. Both coils are wound co-axial with respect to the examined pipe, and are separated by a distance greater than two (2) times the pipe diameter. The actual separation depends on the application, but will always be a minimum of 2 pipe diameters. It is this separation that gives RFT its name - the detector measures the electromagnetic field remote from the exciter. Although the fields have become very small at this distance from the exciter, they contain information on the full thickness of the pipe wall.

The detector electronics include high-gain instrumentation amplifiers and steep noise filters. These are necessary in order to retrieve the remote field signals. The detector electronics output the amplitude and phase of the remote field signal to an on-board storage device. The data is recalled for display, analysis, and reporting purposes after the examination process is completed.

**Figure 3-16. See Snake® (One of three modules)**



(Courtesy of Russell NDE Systems Inc.)

**Figure 3-17. Schematic of Magnetic Interaction between RFT Tool and Pipe**

**3.3.3 External Inspection Technology Description.** External condition assessment tools provide detailed condition information for selected locations along the pipeline and then rely on statistical methods to predict the condition of the entire pipeline segment. Often the detailed external assessments are supplemented with soil corrosivity and coating condition data to improve confidence in the statistical predictions. Although these technologies are capable of inspecting the entire pipeline length, that would require excavation of the full length of the pipeline which is rarely practical.

External inspection of pipelines has been widely used because it allows the pipeline to remain in service while the localized condition of the pipe is being assessed. Often small areas around the pipe must be cleared because the sensors on the device need to have contact with the outside pipe surface.

**AESL ECAT.** The AESL pipeline assessment process identifies existing leakage failure patterns and the likelihood of structural failure to predict future growth of these failure modes. Inspection is carried out externally at selected pipeline locations using a range of AESL designed 'high flux' (HF) magnetic flux leakage inspection tools and commercial ultrasonic instruments.

Typically, AESL conducts an initial assessment of the pipeline route and ground conditions to select the optimum locations to inspect the pipeline[8]. Then, the pipeline is inspected to identify and provide location, sizing, and imaging of internal and external defects, which are differentiated by proximity sensors. Inspection begins with spot readings of original wall thickness and coating condition in a pre-defined grid pattern (see Figure 3-18). Wall thickness measurements are taken using conventional ultrasonic inspection tools, while pipeline coating condition is assessed visually. Wall condition assessment is then completed using ECAT over 1 m long lengths around the pipe circumference[9] (see Figure 3-19). The ECAT is equipped with GPS and blue tooth technology that is used to transfer the data in real-time. Once inspections are complete, AESL applies statistical models developed in-house to predict the condition of long lengths of un-inspected pipe from the results of the few local inspections.

**RSG HSK and CAP.** The RSG inspection tools use a patented BEM technology to assess localized pipeline condition in ferrous pipes. These technologies work by inducing a broadband eddy current pulse in the pipe wall; the decay of the eddy currents are measured with sensors to determine the remaining wall thickness and fractures (Liu et al., 2012). Sensors can be as small as a 1 $\text{in}^2$ and can detect corrosion pitting as little as 10% of the wall thickness over the entire sensor aperture; corrosion with length and width smaller than the aperture will produce a proportionally smaller signal. Since the electromagnetic field can penetrate depths 2.5 times the diameter of the transmitter, it is not necessary for the inspection system to be in close contact with the pipe; some dirt on the outside of the pipe is acceptable as long as the system indicates an acceptable signal is attained. This is advantageous for piping systems that are coated, lined, or insulated. Data can be obtained in real-time or stored for later processing and analysis. Often, comparisons are made between real-time and processed data to ensure quality of on-site reports.

During the field demonstration, RSG demonstrated two surface scanning systems, one is a fully commercially available HSK, which externally scans along the length of the pipe as well as around the pipe circumference (see Figure 3-20); the other is a keyhole inspection system called the CAP, which at

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[8] This was not possible during the field demonstration as the inspection locations were predetermined for logistical reasons.

[9] The amount of circumferential coverage depends on the pipeline diameter. For pipe diameters less than or equal to 6-in., full circumferential inspection is provided. For pipe diameters greater than 6-in., inspection is conducted over 105 mm wide increments.

the time of the demonstration was not commercially available (see Figure 3-21). The HSK is a line of sensors that is manually moved around the pipe to make a 2 dimensional image. The CAP has a 2-dimensional array of sensors and records an image with one placement by sequencing through the sensors. The HSK is an in-the-ditch method designed to examine part or full circumference of the pipe depending on what is possible to expose. The CAP is capable of scanning the portion of pipe exposed via the excavation from the street, which in this demonstration was a small excavation exposing only the crown of the pipe.

**Figure 3-18. Grid Pattern Used for Ultrasonic Wall Thickness Measurements and Coating Assessment**

Figure 3-19.  AESL ECAT

Figure 3-20.  RSG Hand Scanning Kit (HSK)

Figure 3-21.  RSG Crown Assessment Probe (CAP)

Advantages of the RSG's HSK and CAP external inspection systems include:

- Scanning is not limited by the diameter of the pipe.
- Capable of surveying through thick coatings (50 mm+) such as paint or tar commonly found on pipelines.
- The line can remain in service as readings are taken from the external pipe surface.
- Negligible effect of outside stray current fields potentially contaminating resulting data. Where stray fields are identified (these can be clearly seen in captured data – variations in data capture parameters are possible since the device is non-frequency dependent).

**3.4 Site/Test Preparation. Several activities were necessary prior to, during, and after the field demonstration to accommodate the various technology vendors/visitors and to verify the inspection conditions. The following sections detail specific measures taken to make the demonstration successful for all that participated.**

Prior to the actual demonstration, the condition of the test pipe was relatively unknown, aside from basic pipeline location data and information obtained during previous leak investigations. In June 2009, the valves at both ends of the 2,057-ft test pipe were closed to evaluate if there was any significant pressure drop in the system. This assessment showed that the line maintained a nominally constant pressure for a full day, so it was quite possible that there were no large natural leaks in the test pipe. The leak testing portion of this demonstration revealed only one large leak at a bell and spigot joint and less than a dozen smaller leaks. Leaks at the main supply valve may have provided sufficient water to make up for the leaks from corrosion or at joints. Because of the observations from opportunistic excavations for maintenance, repair, and tapping; leak testing results; and, the ability to hold pressure, it was not anticipated that there would be many large wall corrosion defects in the barrel of the pipe.

### 3.4.1 Access Requirements

**Acoustic Pipe Wall Assessment.** The internal leak detection/location and inspection technologies required only the installation of relatively small taps (2 to 4-in. in diameter) for the insertion and extraction of the inspection tools. However, the in-line, RFEC inspection technology (PipeDiver®) demonstration required installation of a 12-in. diameter tap and gate valve with a mechanical joint (MJ) fitting at each end of the test pipe for insertion and retrieval. Therefore, reducers were used for the demonstration to transition between the access requirements for internal leak detection/location and pipe-wall screening equipment and the 12-in. MJ fitting for PipeDiver®.

For the Sahara® WTT, a 12-in. MJ to 6-in. MJ reducer and a 6-in. MJ cap with a 2-in. National Pipe Thread (NPT) tap were used.

SmartBall™ required either a 4-in. or 6-in. American National Standards Institute (ANSI) flange for a gate valve to launch its equipment. To achieve this set-up, a 12-in. MJ to 6-in. MJ reducer and a 6-in. MJ to 6-in. ANSI flange were used because this equipment could be easily provided by LWC. LWC supplied all pipe fittings for the demonstration. Video inspection methods confirmed the pipe did not have any internal obstructions such as tuberculation, which may have impeded the application of internal inspection technologies.

ThicknessFinder required direct access to the pipe exterior for placement of accelerometers at approximately 300 ft intervals. The intervals were achieved through five large excavation sites and six smaller excavated holes. In addition, Echologics required the gate valves isolating the test pipe to be in the open position to prevent reflection of the induced acoustic wave. A summary of all access requirements is provided in Table 3-2.

**Table 3-2. Summary of Test Pipe Access Requirements for LWC Demonstration for Wall Thickness Screening Technologies**

| Vendor | Type of Inspection | Technology/ Product | Flow Requirements/ Pipeline Constraints | Pipe Access Requirements |
|---|---|---|---|---|
| PPIC (now part of Pure) | Internal; tethered | Sahara® Wall Thickness Testing (WTT) | Flow must be >1 ft/s for single 2-in. diameter tap; Mule tape is required in no-flow situations or when flow is insufficient.<br>At lower flows, the parachute is unable to overcome the drag of the cable for a given distance. | For internal access, One per inspection interval (every 2,500 ft for LWC demonstration; up to 6,000 ft based on Sahara® maximum cable length).<br>A 2-in. diameter (or larger) tap with female NPT thread reducer located at upstream to the section to be inspected;<br>~10 ft clearance to mount insertion equipment.<br>Direct external access to the top of the pipe for sound generation every 250 to 400 ft. |
| Pure Technologies | Internal | SmartBall™ Pipe Wall Assessment (PWA) | Requires appurtenances along pipeline to place receivers<br>Flow range reported at time of demonstration was > ~0.8 ft/s, but < ~1.5 ft/s;<br>Note: Pure reports inspections as low as 0.5 ft/s and as high as 7 ft/s. | Two per inspection interval (at beginning and end of inspection).<br>4-in. or 6-in. diameter clear bore gate valve.<br>> 8 ft vertical clearance at launch tap and > 12 ft vertical clearance at retrieval tap.<br>Both taps at 12 o'clock position.<br>Pulsers installed approximately every 1,000 ft. |

| Vendor | Type of Inspection | Technology/ Product | Flow Requirements/ Pipeline Constraints | Pipe Access Requirements |
|---|---|---|---|---|
| Echologics Engineering | External | ThicknessFinder | Requires appurtenances and/or pipe access to place sensors<br>Requires air to be removed from the line. Requires gate valves to be in the open position to prevent reflection of induced acoustic wave. | Two per inspection interval. Accelerometers require solid contact with the pipe exterior.<br>Pipe access every 200 to 500 ft |

**Internal Inspection.** This section summarizes the pipe access and other requirements for deployment of the internal inspection technologies.

For the PipeDiver® in-line inspection technology demonstration, a 12-in. diameter tap and gate valve with MJ fitting was installed at each end of the test pipe to install insertion and retrieval tubes. These insertion and retrieval tubes measure over 20 ft in height and 12 in. in diameter and require a vertical clearance of over 40 ft at the PipeDiver® launch and retrieval locations.

See Snake® required removal of an 8 ft section from the launch and retrieval points to insert and remove the equipment from the test pipe during the demonstration. The device was pulled through the drained and swabbed pipe with a cable. Modifications are planned to enable un-tethered inspection in a full pipe.

The Sahara® Video technology required only the installation of a 2-in. diameter tap for the insertion and extraction of the tool. Modifications were made to the 12-in. MJ fitting to facilitate launching of the Sahara® Video equipment. Specifically, a 12-in. MJ to 6-in. MJ reducer and a 6-in. MJ cap with a 2-in. NPT tap was used. LWC supplied all pipe fittings for the demonstration. The access requirements for all three technologies are summarized in Table 3-3.

### Table 3-3. Summary of Test Pipe Access Requirements for LWC Demonstration for Internal Inspection Technologies

| Vendor | Type of Inspection | Technology/ Product | Flow Requirements/ Pipeline Constraints | Pipe Access Requirements |
|---|---|---|---|---|
| PPIC<br>(now part of Pure) | Internal; tethered | Sahara® Video | Flow must be >1 ft/s for single 2-in. diameter tap; Mule tape is required in no-flow situations or when flow is insufficient.<br>At lower flows the parachute is unable to overcome the drag of the cable for a given distance. | A single 2-in. diameter (or larger) tap with female NPT thread reducer located at upstream end;<br>~10 ft clearance to mount insertion equipment. |
|  | Internal | PipeDiver® | Butterfly valves > 30-in. in diameter<br>Consistent flow rate with a minimum of 0.7 ft/s and maximum flow rate ~1.5 ft/s for data collection | Two 12-in. diameter taps at each end of inspection region with > 40 ft vertical clearance above taps.<br>Requires flatbed truck and crane to move ~3,000 lb |
| Russell NDE Systems Inc. | Internal | See Snake® | Cleaning pig; boom truck to lower tool; need 8 ft long tray at open ends of main; machined, flat bottom defects to be spaced 5-in. apart for calibration | Two excavations with clearance for 8 ft pipe removal |

**External Inspection.** In general, the ECAT and HSK external inspection tools require exposure of a 4 to 6 ft length of pipe with at least 1 ft circumferential clearance every 300 to 2,500 ft along the pipeline. To accommodate these requirements, three excavation pits were selected by EPA's contractor along the test pipe based on location constraints and some preliminary condition assessment data. To accommodate RSG's CAP system, five smaller excavated holes were created and spaced at regular intervals along the test pipe (approximately every 300 ft). These access requirements for the external inspection technologies are listed in Table 3-4.

**Table 3-4. Summary of Test Pipe Access Requirements for LWC Demonstration for External Inspection Technologies**

| Vendor | Type of Inspection | Technology/ Product | Pipeline Constraints | Pipe Access Requirements |
|---|---|---|---|---|
| Advanced Engineering Solutions, Ltd. (AESL) | External | External Condition Assessment Tool (ECAT) | May require removal of coating; soil and surface conditions | At least three excavations with 2 ft circumferential clearance |
| Rock Solid Group (RSG) | External | Hand Scanning Kit (HSK) | Excess soil removed from the pipe surface; residue soil , surface corrosion, and coating can remain | At least three excavations with at least 1 ft circumferential clearance |
|  | External | Crown Assessment Probe (CAP) | Typical vacuum excavated holes 8-in. in diameter<br>Excess soil removed from the pipe surface; residue soil , surface corrosion, and coating can remain | At least three vacuum excavated 8-in. diameter holes |

### 3.4.2 Safety, Logistics, Excavation, and Tapping

**Safety and Logistics.** During the demonstration, MAC Construction (LWC's contractor) was responsible for traffic rerouting and control. All technology demonstrations occurred on weekdays during normal business hours. While the demonstration was ongoing, portions of Westport Road were closed to through traffic, with some access allowed for local businesses. At the end of each day, MAC Construction plated all open excavations during the evenings and weekends and reopened both lanes of traffic on Westport Road.

A construction trailer (see Figure 3-22) equipped with electrical power provided a work space for the inspection technology vendors, as well as equipment storage during the demonstration. At least one EPA contractor was on site each day of the demonstration and coordinated the dissemination of safety and contact information to the technology vendors and visitors. All logistical and operational questions were handled by the EPA contractor. The EPA contractor also coordinated daily activities with the technology vendors, MAC Construction foreman, and LWC inspectors to ensure that the demonstration ran efficiently and effectively.

Several visitors, including representatives of the EPA and utility companies, came to the site during the demonstration. Visitors were instructed to pre-register via e-mail and sign in with the EPA contractor at the construction trailer before going on site. Safety gear including hard hats, steel-toed shoes and safety vests was required before visitors could gain access to the demonstration site.

Figure 3-22. Construction Trailer for Equipment Storage and Work Space

**Excavation.** Five large excavations were used for the various technologies during the demonstration; these included Pits 1 through 5 as shown in Figure 3-23 and described in Table 3-5. These sites were selected based solely on location along the test pipe. Since the condition of the pipe was initially unknown, EPA's contractor machined several metal loss defects within Pits 2, 4, 5, and F[10] to facilitate tool calibration and to ensure defects were available to find during inspection. Six small excavations, identified as Pits A, B, C, D, E, and F in Figure 3-23, were used to demonstrate one leak detection system and several other condition assessment technologies. Pictures of pre-excavation locations for Pits 1, 2, and 3 are shown in Figures 3-24 through 3-26.

Three large excavations were used for the external condition assessment technologies during the demonstration including Pits L, 2, and F as shown in Figure 3-23 and described in Table 3-5. These sites were selected based on location constraints; Pit L was near an excavation to confirm the largest leak detected in first few weeks of the demonstration. Since the condition of the pipe was initially unknown, EPA's contractor machined several metal loss defects within Pit 2 and Pit F to facilitate tool calibration and to ensure defects were available to find during inspection. Also, small pit-like metal-loss defects were installed in Pit 4 and 5.

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[10] Although calibration defects were machined into Pit F, these were not installed until week three of the demonstration and therefore were not available during the Sahara® Wall Thickness Assessment and Echologics initial visit to the demonstration site. Pit F was originally planned to be a keyhole excavation; however a significant amount of external corrosion was found within the pit and it was decided to make the pit larger for the external condition assessment technologies discussed in this report.

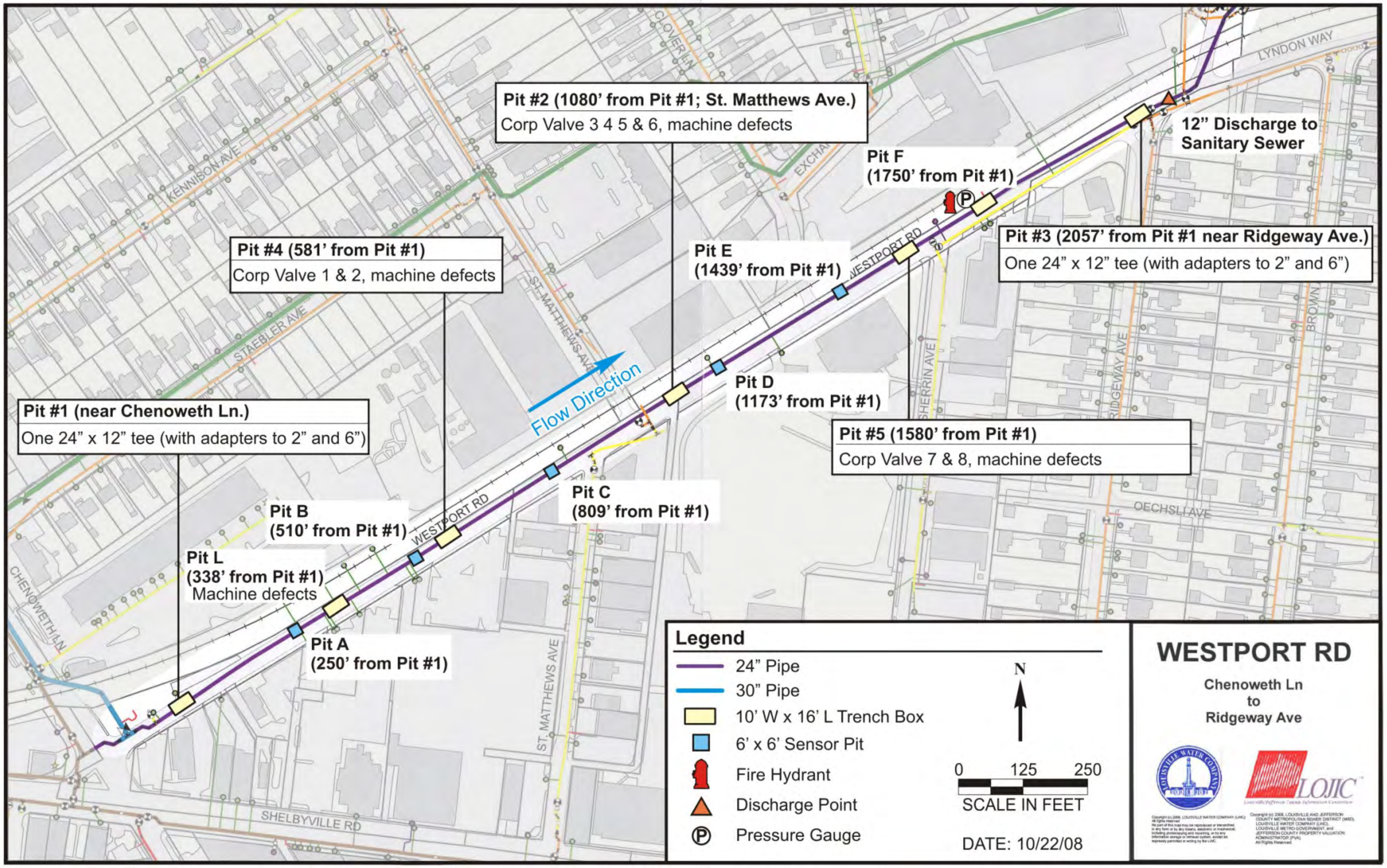


Figure 3-23. Location of Pits for Demonstration

### Table 3-5. Summary of Access Pits – Description and Purpose

| Pit ID | Description | Purpose |
|---|---|---|
| Pit 1 | • Near Chenoweth Lane at location of first 24-in. × 12-in. tee<br>• 8 ft of pipe exposed<br>• Reference point – 0 ft | • Launch internal inspection technologies<br>• Install 12-in. service tap; attach 12-in. × 2-in. and 12-in. × 6-in. reducers to allow access for internal tools |
| Pit 2 | • Intersection of Westport Road and St. Matthews Avenue<br>• ~1,080 ft from first 24-in. × 12-in. tee in Pit #1<br>• ~8 ft of pipe exposed; ~2 ft circumferential clearance | • Install four 1-in. service taps for leak simulations<br>• Install two calibration metal loss defects*<br>• Install nine additional metal loss defects for condition assessment* |
| Pit 3 | • Near Ridgeway Ave. at location of second 24-in. × 12-in. tee<br>• ~2,057 ft from first 24-in. × 12-in. tee<br>• 8 ft of pipe exposed | • Retrieve internal inspection technologies<br>• Install 12-in. service tap; attach 12-in. × 2-in. and 12-in. × 6-in. reducers to receive internal tools<br>• Install 12-in. tee to divert flow to storm/sanitary sewer |
| Pit 4 | • ~581 ft from first 24-in. × 12-in. tee<br>• 3 ft of pipe exposed; top half only | • Install two, 1-in. service taps for leak simulations<br>• Install pit-like metal-loss defects for condition assessment* |
| Pit 5 | • ~1,580 ft from first 24-in. × 12-in. tee<br>• 3 ft of pipe exposed; top half only | • Install two, 1-in. service taps for leak simulations<br>• Install pit-like metal-loss defects for condition assessment* |
| Pit A | • ~250 ft from first 24-in. × 12-in. tee in Pit #1<br>• ~3 ft of pipe exposed; top portion only | • Small excavation for LeakFinderRT, keyhole condition assessment technologies and soil sampling* |
| Pit B | • ~510 ft from first 24-in. × 12-in. tee in Pit #1<br>• ~3 ft of pipe exposed; top portion only | • Small excavation for LeakFinderRT, keyhole condition assessment technologies and soil sampling* |
| Pit C | • ~809 ft from first 24-in. × 12-in. tee in Pit #1<br>• ~3 ft of pipe exposed; top portion only | • Small excavation for LeakFinderRT, keyhole condition assessment technologies and soil sampling* |
| Pit D | • ~1,173 ft from first 24-in. × 12-in. tee in Pit #1<br>• ~3 ft of pipe exposed; top portion only | • Small excavation for LeakFinderRT, keyhole condition assessment technologies and soil sampling* |
| Pit E | • ~1,439 ft from first 24-in. × 12-in. tee in Pit #1<br>• ~3 ft of pipe exposed; top portion only | • Small excavation for LeakFinderRT, keyhole condition assessment technologies and soil sampling* |
| Pit F | • ~1,750 ft from first 24-in. × 12-in. tee in Pit #1<br>• ~20 ft of pipe exposed; ~2-ft circumferential clearance | • Small excavation for LeakFinderRT, keyhole condition assessment technologies and soil sampling; significant graphitization was found when excavated*<br>• Install one large calibration defect (metal-loss defect ~ 6 1/8 in. long; 0.28 to 0.45 in. depth)* |
| Pit L | • 326 ft from first 24-in. × 12-in. tee in Pit 1<br>• ~14 ft of pipe exposed; ~2 ft circumferential clearance | • Large leak detected<br>• A large leak was verified at the bell and spigot joint. |

* These pits were created for demonstration of condition assessment technologies, but were also used to demonstrate the external leak detection technology (LeakFinderRT).

Figure 3-24.  Location of Pit 1 – Near Chenoweth Lane

Figure 3-25.  Location of Pit 2 – Near St. Matthews Ave

Figure 3-26. Approximate Location of Pit 3 – Near Ridgeway Avenue

Five small excavations were used for external condition assessment. RSG used these locations with their CAP technology. AESL used these locations for soil sampling. These locations were Pits A, B, C, D, and E. Soil measurements were also taken by AESL in Pit 1 and Pit 3, which were used for launching the internal inspection and leak detection tools.

Figure 3-27. Test Pipe Discharge to Storm Sewer Configuration

**Generating Flow**. While some of the inspection technologies require flow to detect and locate leaks, the test pipe was no longer supplying water to customers in anticipation of the pending replacement project. Therefore, to create flow during the demonstration, water was supplied to the test pipe through a valve near Chenoweth Lane connected to a 30-in. diameter line with a pumping station within a mile. At the end of the test pipe, the flow was diverted to the sanitary sewer through a 12-in. gate valve and high density polyethylene (HDPE) line located downstream of Pit 3 (see Figure 3-27).

There were two drawbacks to this arrangement. First, the discharge was essentially a very large leak that created noise during the demonstration and which added to the background noise recorded by the acoustic sensors; the effects of which became more pronounced as technologies neared the discharge point. Second, because the discharge was diverted to the combined sewer, it could not be used immediately after heavy rainfall to prevent sewers from overflowing. Rain delayed several of the demonstrations with a record rainfall of 6.5-in. on August 4, 2009, causing a 2 ½-day delay.

**Internal Inspection Test Pipe Opening/Cut-out.** Prior to the inline inspection by Russell NDE Systems Inc., an 8 ft section of the pipe was removed from Pit 1 and Pit 3 to allow for access to the pipe interior; this included removal of the 12-in. tee section plus some additional pipe. At the time of the demonstration, the prototype See Snake® used a winch and cable to pull the tool through the pipeline rather than being transported by the water flow. The line had to be emptied and a foam pig was used to remove water that collected in the low spots.

Prior to the See Snake® demonstration, a video inspection of the test pipe was conducted by Pipe Eyes, LLC to identify any significant pipe restrictions that would prevent a successful demonstration of the See Snake® technology. Since no restrictions were found, a tether was inserted in the test pipe using the water flow to eventually thread the pull cable (mule tape) once the line was dewatered. A wooden support system was provided for launching and receiving the See Snake® technology. Additional equipment included a backhoe to raise and lower the tool into the pit, as well as the winch and cable system to pull the tool through the pipeline.

### 3.4.3 Machined Defects.

A milling machine on a magnetic base shown in Figure 3-28 was used to create several machined metal loss defects that were installed in Pit 2, Pit 4, Pit 5, and Pit F. The intent of installing machined corrosion defects was: (a) to provide defects for vendors to calibrate their inspection devices, and (b) to create a set of "hidden" defects whose characteristics were only known by the EPA contractor, not the inspection vendor. The intent was to produce external defects ranging from simple to difficult to detect and/or size for in-line and external electromagnetic inspection technologies. In this way, the demonstration could help to define both the current capability and future challenges for each of the inspection technologies. Some wall thickness assessment technologies only identify average changes in wall thickness over a specified pipe length and therefore are not intended to find individual defects unless the defect is large enough to cause a significant change in the pipe wall hoop stress.

**Figure 3-28. Magnetic Base End Mill Used to Create Machined Defects**

The calibration defects were provided to the inspection vendors for system verification and calibration to facilitate subsequent analysis and post-processing. The manufactured defect sizes ranged from approximately 1- to 3-in. in length with depths varying between 20% up to 70% wall loss; the Pit F defect was four closely spaced pits with a 6-in total length. All machined defects (except the calibration defects) were filled with a non-conductive material to dissuade the vendors from manually measuring the defects in the ditch. The machined defect configurations for Pit 2, Pit 4, Pit 5 and Pit F are shown in Figures 3-29 to 3-32, while descriptions and photos of each unknown machined defect are provided in Tables 3-7 to 3-9. During installation of these defects significant areas of natural corrosion were found in the line. As such, the machined defects were placed as to not disturb the natural corrosion.

**Table 3-6. Calibration Defects Provided to Technology Vendors**

| Calibration Defect ID | Location (ft) | Degree | Length (in.) | Width (in.) | Depth (in.) | Photo |
|---|---|---|---|---|---|---|
| 2-0-1 (cal) | 1081 | 0° | 2.75 | 1 | 0.28 |  |
| 2-0-2 (cal) | 1082 | 0° | 1.3125 | 1.3125 | 0.44 |  |
| F-0-1 (cal) – 4 closely spaced pits | 1750.7<br>1750.8<br>1750.9<br>1751.0 | 0° | 1.25<br>1.4375<br>1.5<br>1.75 | 1.25<br>1.4375<br>1.5<br>1.75 | 0.28<br>0.36<br>0.40<br>0.45 |  |

**Table 3-7. Hidden Defects for Inspection – Pit 2**

| Defect ID | Location (ft) | Degree | Length (in.) | Width (in.) | Depth (in.) | Photo |
|---|---|---|---|---|---|---|
| 2-45-1 | 1081.5 | 45° | 2.25 | 1 | 0.36 |  |

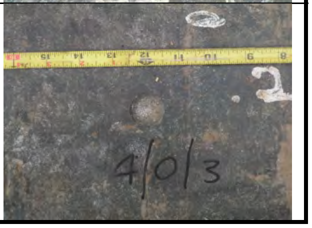
## Table 3-7. Hidden Defects for Inspection – Pit 2 (Continued)

| Defect ID | Location (ft) | Degree | Length (in.) | Width (in.) | Depth (in.) | Photo |
|---|---|---|---|---|---|---|
| 2-45-2 | 1082.6 | 45° | 2.9375 | 1 | 0.26 |  |
| 2-45-3 | 1083.7 | 45° | 1.0 | 1 | 0.53 |  |
| 2-45-4 | 1084.6 | 45° | 3.75 | 1 | 0.23 |  |
| 2-45-5 | 1085.5 | 45° | 1.25 | 1.25 | 0.50 |  |
| 2-90-1 | 1082.0 | 90° | 2.3125 | 1 | 0.41 |  |
| 2-90-2 – 2 closely spaced pits | 1083.1 | 90° | 1.75<br>1.9375 | 1 | 0.12<br>0.14 |  |
| 2-90-3 | 1084.1 | 90° | 3.0 | 1 | 0.19 |  |

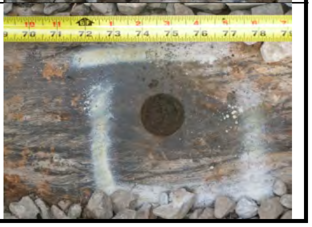
## Table 3-7. Hidden Defects for Inspection – Pit 2 (Continued)

| Defect ID | Location (ft) | Degree | Length (in.) | Width (in.) | Depth (in.) | Photo |
|---|---|---|---|---|---|---|
| 2-90-4 | 1085.1 | 90° | 2.3125 | 1 | 0.35 |  |

## Table 3-8. Hidden Defects for Inspection – Pit 4

| Calibration Defect ID | Location (ft) | Degree | Length (in.) | Width (in.) | Depth (in.) | Photo |
|---|---|---|---|---|---|---|
| 4-0-1 | 577.1 | 0° | 1.0625 | 1.0625 | 0.32 |  |
| 4-0-2 | 578.4 | 0° | 1.375 | 1.375 | 0.37 |  |
| 4-0-3 | 579.4 | 0° | 1.25 | 1.25 | 0.24 |  |

### Table 3-9. Hidden Defects for Inspection – Pit 5

| Calibration Defect ID | Location (ft) | Degree | Length (in.) | Width (in.) | Depth (in.) | Photo |
|---|---|---|---|---|---|---|
| 5-0-1 | 1580.5 | 0° | 1 | 1 | 0.23 |  |
| 5-0-2 | 1581.7 | 0° | 1 | 1 | 0.41 |  |
| 5-0-3 | 1586.2 | 0° | 1 | 1 | 0.45 |  |

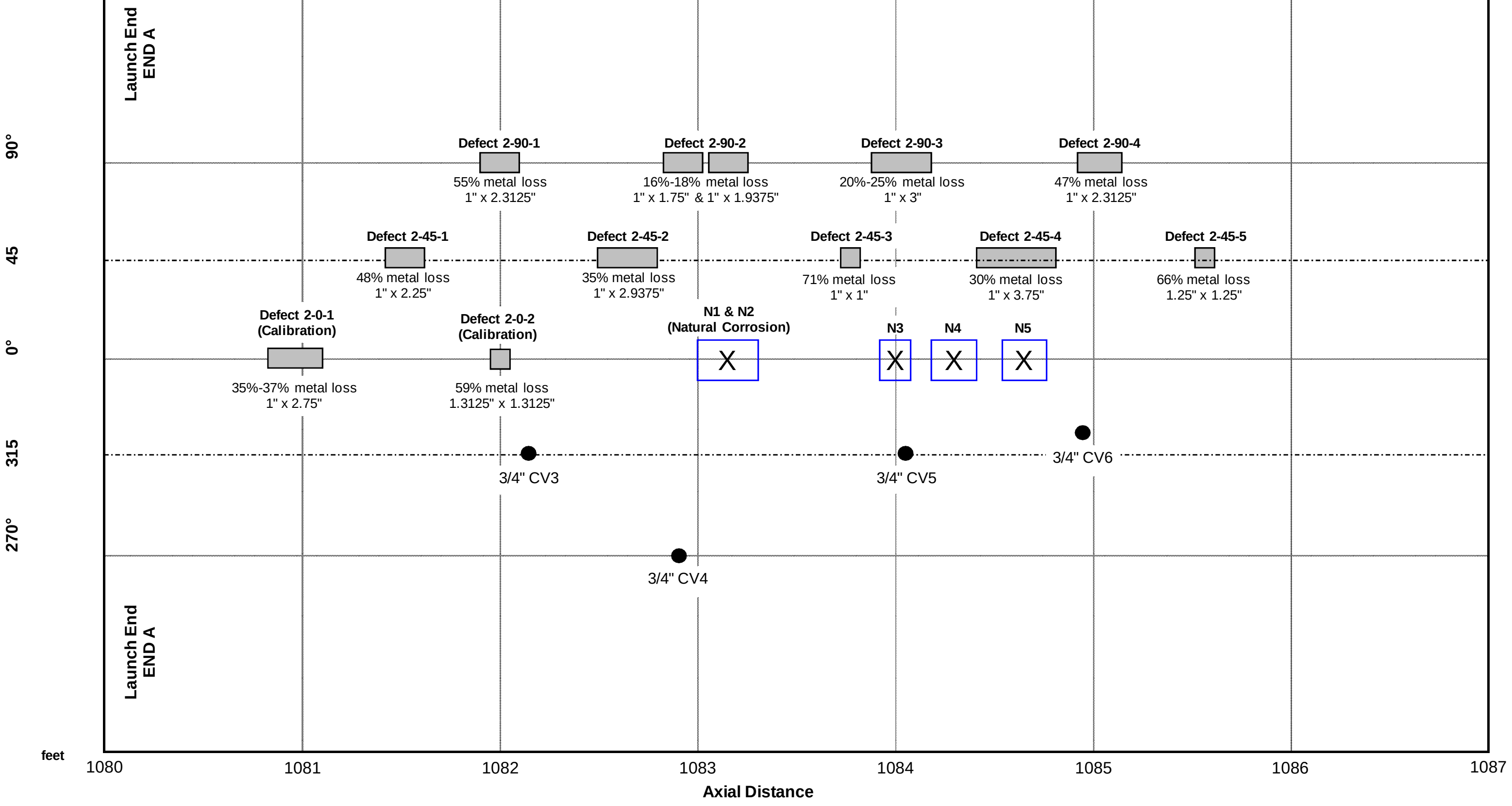


Figure 3-29. Machined Defect Locations in Pit 2

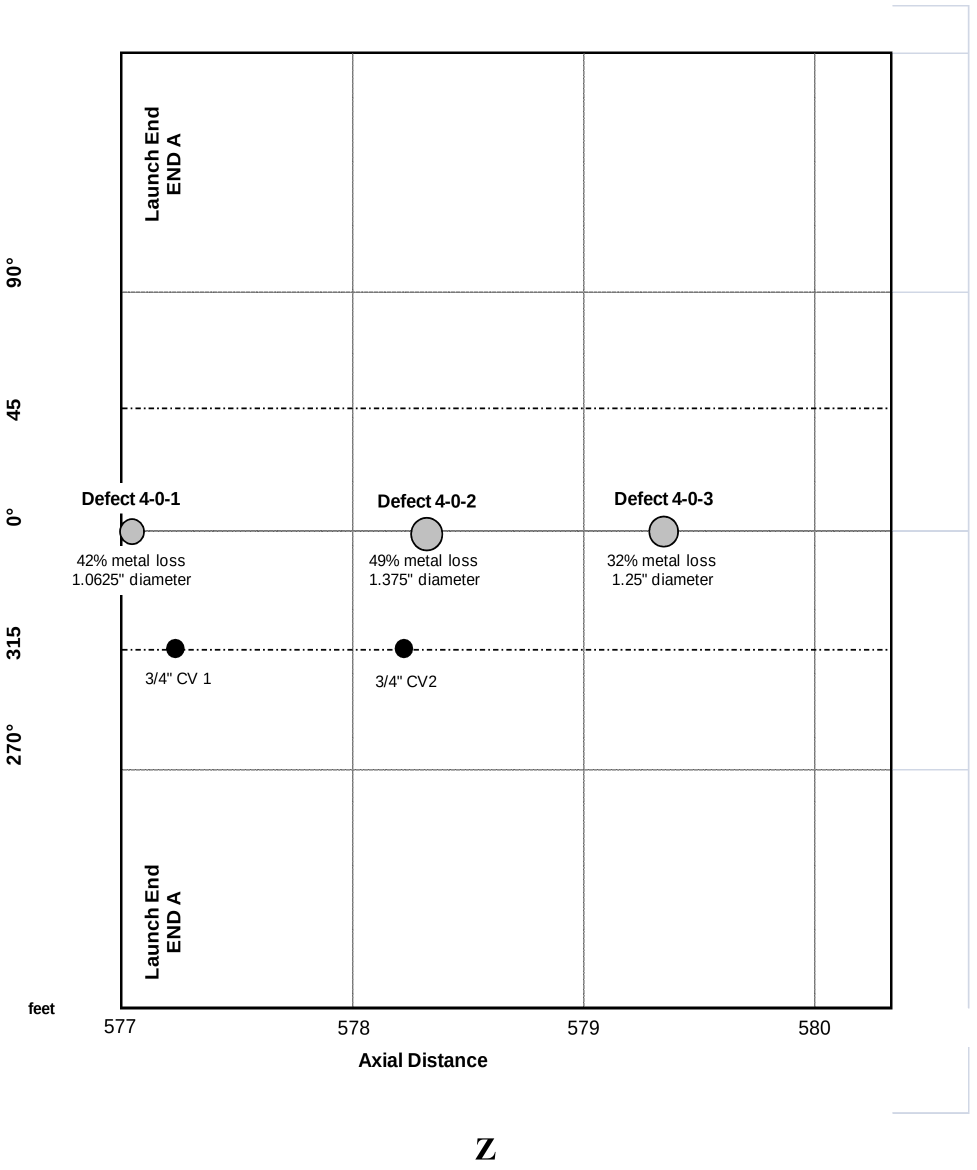


Figure 3-30. Machined Defect Locations in Pit 4

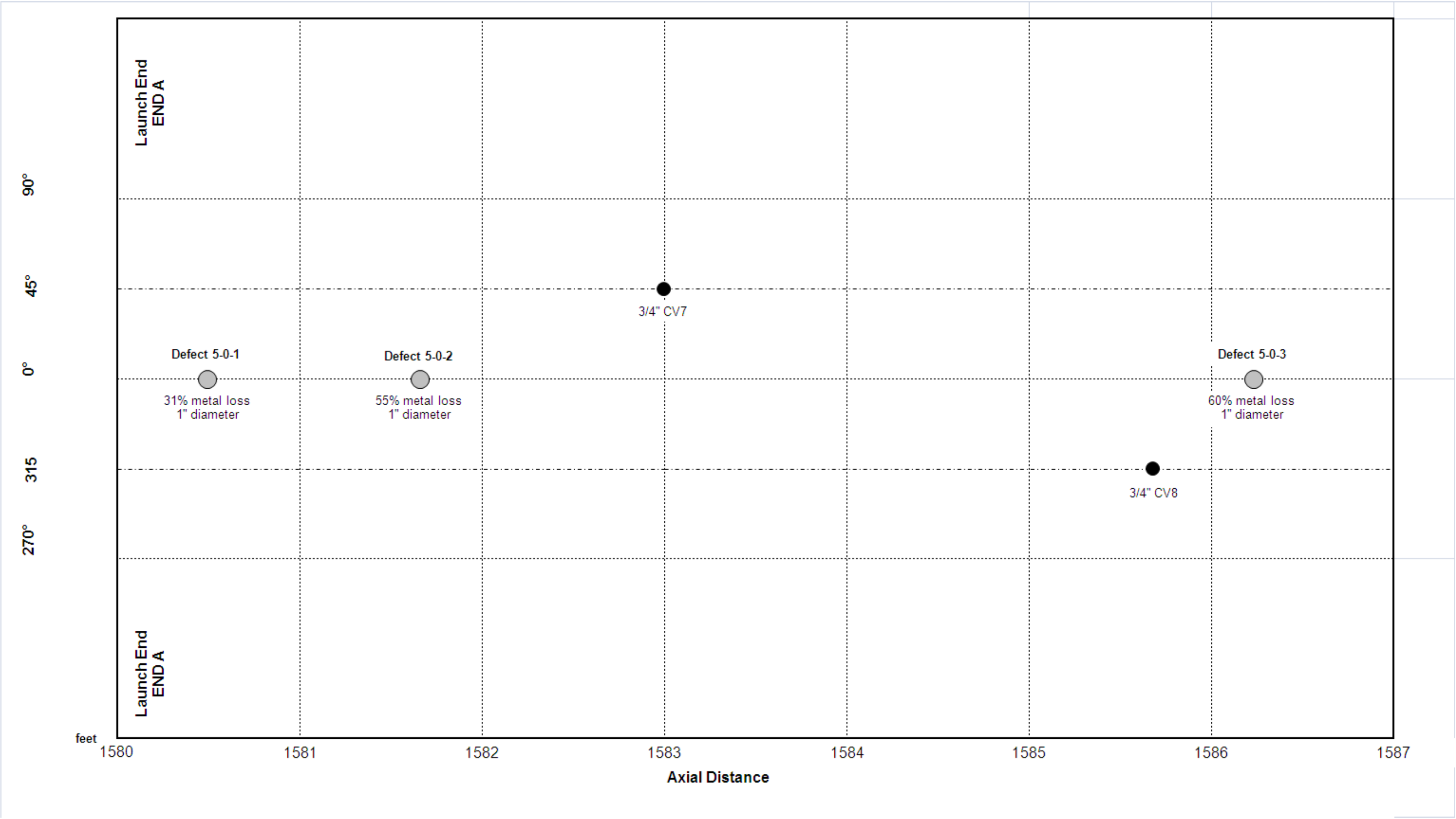


**Figure 3-31. Machined Defect Locations in Pit 5**

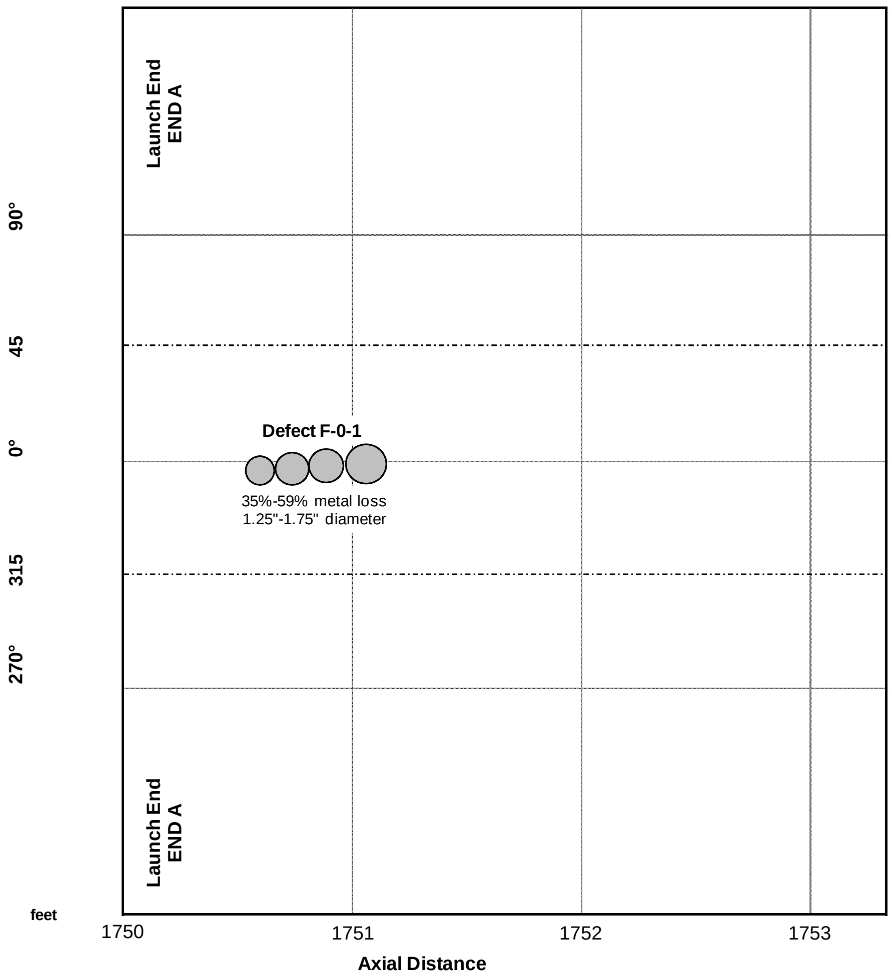


Figure 3-32. Machined Defect Locations in Pit F

## 3.5 Test Configuration

**3.5.1 Pipe Wall Assessment.** Three vendors participated in the water main inspection demonstration for acoustic wall thickness assessment technologies on the following dates:

- ThicknessFinder – On site from July 6, 2009 through July 8, 2009 then again August 10, 2009 through August 12, 2009[1]
- Sahara® Wall Thickness Testing – On site from July 13, 2009 through July 17, 2009; wall thickness assessment on July 16 and July 17.
- SmartBall™ PWA – On site from August 3, 2009 through August 7, 2009[2]

The activities conducted each day are provided in Table 3-10.

**Table 3-10. Daily Activities for Each Wall Thickness Assessment Technology Vendor**

| Date | Daily Activities |
|---|---|
| ***ThicknessFinder – One operator*** | |
| Jul. 6 | • Checked-in at demonstration site and set-up equipment<br>• Unable to complete noise test; background levels appeared low |
| Jul. 7 | • Installed sensors (accelerometers) in Pits 1 and 3 with receiver in Pit C<br>• Assessed background noise; added filters<br>• Reconfigured to 1,000 ft<br>• Pipe pressure at 53 psi<br>• Suspected that the pipe had air pockets because could not get a clear signal; tried to swap RF transmitters |
| Jul. 8 | • Still unable to get a good signal; prior experience by the vendor suggested that the cause of the poor signal may have been air in the line.<br>• Opened fire hydrant to purge air from line; milky water observed.<br>• Did not get any data; arranged to come back at a later date |
| Aug. 10 | • Checked-in at demonstration site and set-up equipment |
| Aug. 11 | • Condition assessment for pipe from Pits 1, 2, and 3 using accelerometers<br>• Found one large leak and one or two smaller leaks |
| Aug. 12 | • Hydrophones placed in various pits to conduct leak detection<br>• Pipe pressure between 52 and 54 psi<br>• Road traffic near pits caused noise interference. Test repeated.<br>• Packaged equipment for shipping |

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[1] Because a significant amount of air was in the line during their first visit to the demonstration site, Echologics was unable to get accurate data from their ThicknessFinder and LeakfinderRT technologies. The test pipe was dewatered and cut a few weeks prior to the demonstration to install tees at both ends of the test pipe. While the test pipe was filled and flushed for a few hours upon completion of the tee installation, a video assessment showed that air pockets remained throughout the pipeline. Attempts were made by LWC to remove air from the line and Echologics was permitted to return at a later date to complete their demonstration.

[2] Heavy rain fall occurred on August 4, 2009, preventing LWC from discharging to the storm sewer for 2-1/2 days. As such, Pure was unable to access the pipeline for leak assessment until August 6, 2009.

### Table 3-10. Daily Activities for Each Wall Thickness Assessment Technology Vendor (Continued)

| Date | Daily Activities |
|---|---|
| ***Sahara® –2-3 operators*[13]** | |
| Jul. 13 | • Checked-in at demonstration site and set-up Sahara® Video equipment<br>• Pipe pressure at 56 psi; flow rate ~ 2.6 ft/s with three valve turns<br>• Launched Sahara® Video; parachute failed to deploy and was replaced<br>• Started video inspection; increased flow to keep camera from bouncing (~2-2-½ hours)<br>• Retrieved Sahara® Video equipment (~45 minutes) |
| Jul. 14 | • Launched Sahara® leak detection equipment for calibration survey; natural leaks and simulated leaks detected during all surveys<br>• Conducted second leak detection survey<br>• Pipe pressure at ~58 psi |
| Jul. 15 | • Launched Sahara® leak detection equipment for third and fourth simulated leak surveys |
| Jul. 16 | • Installed accelerometers for condition assessment<br>• Launched Sahara® WTT equipment - hydrophone<br>• Pipe pressure at ~55 psi |
| Jul. 17 | • Finished condition assessment<br>• Pipe pressure at ~55 psi<br>• Conducted leak detection survey with new hydrophones<br>• Prepared for PipeDiver® inspection<br>• Packaged equipment for shipping |
| ***SmartBall™ – Two operators*** | |
| Aug. 3 | • Check-in at demonstration site and set-up equipment |
| Aug. 4 | • Significant rain event; demonstration canceled |
| Aug. 5 | • Significant rain event; demonstration canceled |
| Aug. 6 | • Installed sensors in Pits 1, C, and 3<br>• Installed insertion and extraction tubes<br>• Conducted first SmartBall™ run (~45 minutes)<br>• Conducted second SmartBall™ run (~50 minutes)<br>• Dismantled insertion and extraction tubes |
| Aug. 7 | • Installed insertion and extraction tubes<br>• Conducted first SmartBall™ run (~75 minutes)<br>• Conducted second SmartBall™ run (~53 minutes)<br>• Conducted third SmartBall™ run (~44 minutes)<br>• Dismantled insertion and extraction tubes<br>• Packaged equipment for shipping |

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[13] More were on site for the demonstration. The inspection vendor used the demonstration to train new operators.

**Sahara® WTT.** Five Sahara® insertions were performed from July 13 to July 17 for three different inspection technologies (leak detection, video, and condition assessment) that used the same tether, insertion equipment, and tracking method as the leak detection technology. The equipment arrived by a custom vehicle on the morning of the inspection. The vehicle contained the sensors, cable deployment system, support electronics, and electrical power for conducting video, leak, and condition assessment surveys. Sahara® WTT was performed on July 16 and 17, 2009 in conjunction with Sahara® Leak Detection activities. The Sahara® sensor head was inserted into Pit 1 and secondary external sensors were installed at Pits A, C, E, and 3 to conduct the structural integrity survey. Multiple test reference signals were generated at each of the pits to conduct the wall thickness measurements.

With the proper fittings being installed prior to the inspection, set-up required about 2 hr and tear down required about 1 hr. Set-up and tear down were faster on subsequent days of the demonstration. All of the fittings that touched the water were sprayed with a chlorine solution for sterilization. During several inspections, at the request of the operator, the pipeline flow rate was increased to counteract the increasing weight of the tether so that the sensor head could be carried the entire length of the test pipe.

Throughout the demonstration observers could watch data being collected on computer screens and speak with analysts about the real-time results. A preliminary report was provided to EPA's contractor on August 8, 2009. A final report with the leak detection and structural integrity demonstration results was submitted to EPA's contractor October 14, 2009.

**SmartBall™ PWA.** Five SmartBall™ insertions were performed from August 6 to August 7, 2009, for leak detection and pipe wall thickness assessment. Seven cases of equipment, five suitcase-sized and two long, thin boxes arrived by common overnight delivery service the week prior to the demonstration.

SmartBall™ PWA was performed by launching the equipment in Pit 1, allowing the SmartBall™ to travel with the water flow to conduct the inspection, and then extracting the equipment using an extraction tube in Pit 3. LWC provided a 6-in. ANSI flange on the top of the gate valve in Pit 1 and 3 to which Pure mounted its 4-in. diameter insertion and extraction tubes. Prior to the insertion, Pure verified that adequate flow was available to carry the SmartBall™ the full length of the test pipe in a reasonable amount of time. Flow rates between 1 and 2 ft/s were maintained, resulting in inspection times between 45 minutes and 1 hr.[14] The inspection procedure involved first placing the extraction net in the pipeline, then inserting the SmartBall™. With the proper fittings being installed prior to the inspection, the set-up and tear down process for SmartBall™ required about an hour each. All fittings that touched the water were sprayed with a chlorine solution for sterilization.

Knowing the position of the SmartBall™ within the pipeline is critical for accurately assessing the pipe wall condition and multiple locating methods are used by SmartBall™ to establish the position. Distance profiles are generated to give a rough estimate of the SmartBall™ position over time. Data obtained from the accelerometers and magnetometers on board the SmartBall™ are used to obtain a velocity profile for tracking the tool (see Appendix C for examples of position and velocity data plots). Also, absolute position reference points from above ground locations were obtained from the SmartBall™ Receivers (SBR), which use time-stamped data to track the position of the SmartBall™. Individual SBRs tracked the ball's progress through the pipeline for over 850 ft; the distance and location of the aboveground points were based on information provided to Pure by EPA's contractor. To establish the position of the ball as a function of time, the results of the rotation profile, velocity data, and the SBR tracking are combined to provide a position-versus-time relationship for the entire run of the tool. The exact location of where each SBR was placed along the test pipe during each run is detailed in Table 3-11.

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[14] The SmartBall™ typically travels at about 90 percent of the flow rate. The ball was launched a few minutes after flow was confirmed and stopped after the ball was confirmed to be caught.

**Table 3-11. SmartBall™ Receiver (SBR) Locations**

| Location ID | Distance from Launch (ft) |
|---|---|
| Insertion | 0.0 |
| Midpoint | 809.0 |
| Extraction | 2,057.0 |

Once the ball was launched, observers and technicians waited for the ball to be received at Pit 3. The vendor verbally reported on pipe condition to EPA's contractor the day after each inspection. There were no ongoing activities for the operators to perform as the SmartBall$^{TM}$ traveled through the pipeline. A final report of leak detection and condition assessment results was provided on August 14, 2009.

**ThicknessFinder.** From July 6 through July 8, 2009, Echologics was on site to demonstrate its ThicknessFinder and LeakFinderRT technologies. These initial inspections were unsuccessful because they suspected air in the line.[15] Echologics was rescheduled and returned August 10 through 12 to have a second chance of demonstrating these technologies. The condition assessment was conducted on August 11 and 12. One Echologics technician arrived the day of the inspection with two cases of equipment the size of a common suitcase in the back of a small rented vehicle.

Echologics used the following survey methodology to conduct their wall thickness assessment:

1. For each location surveyed, sensor locations were chosen and the distance between the locations were measured. A very accurate measurement of the distance between sensors is required. Although less important for leak detection measurements, an error in measurement of even 3 ft over a 300 ft distance can lead to errors of 15% in wall thickness estimation. The margin of error acceptable is dependent on the pipe type and the distance between sensors. There were some cases where accurate pipe geometry was not available. For example, elevation changes and curves in the road may create discrepancies between Echologics' distance measurement along the surface and the physical distance of the pipe underground. Any locations that presented this difficulty were noted and discussed in the results.
2. Sensors were placed on the chosen locations, either taps that were previously installed or in excavations on the surface of the pipe, and a noise source was created by opening an orifice at a hydrant, typically at a location out-of-bracket (beyond one of the sensors).
3. The temperature of the water was recorded, generally at the time of testing, for each of the test sites since this can influence wave velocity.
4. The data was stored as a raw wave file for further analysis and later confirmation. To confirm data quality for future processing, data was reanalyzed and filtered to obtain an optimum correlation peak.

Wall thickness assessment measurements were performed in pipe section lengths between 250 ft and 360 ft. The assessment lengths were chosen based on typical distances used for commercial leak detection projects conducted by Echologics.

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[15] Because a significant amount of air was in the line during their first visit to the demonstration site, Echologics was unable to get accurate data from their LeakfinderRT technology. The line was dewatered and cut a few weeks prior to the demonstration to install tees at both ends of the test pipe. While the line was filled and flushed for a few hours upon completion of the tee installation, a subsequent video assessment showed that air pockets remained throughout the pipeline.

Additionally, the wave propagation velocity is a function of the total thickness of the pipe wall and the corresponding material elastic modulus. If a pipe is concrete lined, as is the case with the test pipe, the structural stiffness of the pipe is increased via the additional strength of the concrete. The wave velocity then becomes a function of the structural stiffness of the metal and the concrete lining. Therefore, Echologics reports a thickness that is greater than the thickness of the cast metal. This is referred to as the equivalent, effective, or structural thickness and generally it is 0.08-in. to 0.12-in. (2 to 3 mm) thicker than the base metal. For the demonstration, the pipe with an average actual wall thickness of 0.78-in. was determined to have an effective wall thickness between 0.85 and 0.90 inches.

Echologics stated that the accuracy of the ThicknessFinder method may be affected primarily by the accuracy of the measured distance between sensors and the presence of water main repairs (pipe replacement, repair clamps, and collars). Echologics also discussed several other possible sources of error within their demonstration results documentation (see Appendix D). These sources of error include manufacturing wall thickness tolerances, variation on Young's Modulus, inaccurate records, and errors from electronic hardware and digital processing.

3.5.2 Internal Inspection. Three in-line inspection vendors participated in the demonstration on the following dates:

- Sahara® Video – Vendor was on site from July 13, 2009 through July 17, 2009 for leak and wall thickness assessment; video assessment on July 13.
- PipeDiver® – On site from July 20, 2009 through July 29, 2009; Testing not conducted on weekend.
- See Snake® – On site from August 31, 2009 through September 4, 2009; inspections conducted September 3 and September 4, 2009

The activities conducted each day are provided in Table 3-12.

**Table 3-12. Daily Activities for Each Inline Inspection Technology Vendor**

| Date | Daily Activities |
|---|---|
| | **Sahara® Video –2-3 operators[16]** |
| Jul. 13 | • Checked-in at demonstration site and set-up Sahara® Video equipment<br>• Pipe pressure at 56 psi; flow rate ~ 2.6 ft/s with three valve turns<br>• Launched Sahara® Video; parachute failed to deploy and was replaced<br>• Started video inspection; increased flow to keep camera from bouncing (~2-2-½ hours)<br>• Retrieved Sahara® Video equipment (~45 minutes) |

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[16] About twice that number were on site for the demonstration. Vendor used the demonstration for training new operators.

**Table 3-12. Daily Activities for Each Inline Inspection Technology Vendor (Continued)**

| Date | Daily Activities |
|---|---|
| **PipeDiver® – 6 operators** | |
| Jul. 16 | • PipeDiver® equipment delivered to demonstration site and unloaded |
| Jul. 20 | • Check-in at demonstration site and set-up for PipeDiver® inspection<br>• An above ground tracking system was used. Marked ground every 60 ft through 600 ft to try to achieve a tool speed of ~ 1 ft/s. If proper speed achieved, the tool would pass a checkpoint every minute.<br>• Crane did not work properly; made arrangements to have an excavator on site the next day |
| Jul. 21 | • Pipe pressure at 52 psig<br>• Excavator arrived before noon<br>• Extraction tube installed (~45 min)<br>• Insertion tube installed (~30 min)<br>• Sanitizing and filling insertion tube with water (~1 hr)<br>• Launched PipeDiver® but the tool got stuck near the tee tie-in to the pipeline<br>• Aborted launch to review Sahara® Video to determine what was causing the PipeDiver® to get stuck<br>• Removed insertion and extraction tubes (~1-1/2 hr)<br>• Fixed broken paddles and reconfigured the tool to help get it past the ~4” gap between the tee and original pipe identified in the Sahara® Video |
| Jul. 22 | • Significant rain event; demonstration canceled[17] |
| Jul. 23 | • Extraction tube installed (~35 min)<br>• Insertion tube installed (~25 min)<br>• Municipal Sewer Department (MSD) on site to monitor flow to storm sewer during the demonstration<br>• Sanitizing and filling insertion tube with water plus providing overview of technology to visitors (~1-1/2 hr)<br>• Pipe pressure at 54 psig as measured by LWC gauge on hydrant; flow rate ~0.8 ft/s as measured by vendor<br>• Conducted inspection (~45 min); transmitter located in front module, sensors in back module to conduct RFEC inspection<br>• Above ground tracker briefly lost contact with PipeDiver®; flow stopped to relocate<br>• Removed insertion and extraction tubes (~1-1/2 hr) |
| Jul. 24 | • Extraction tube installed (~30 min)<br>• Insertion tube installed (~30 min)<br>• MSD on site to monitor flow to storm sewer during the demonstration<br>• Sanitizing and filling insertion tube with water (~15 min)<br>• Pipe pressure at 54 psig; flow rate ~0.3 ft/s<br>• Conducted inspection (~2 hr); transmitter located in same module as sensors<br>• Removed insertion and extraction tubes (~1 hr) |
| Jul. 27 | • Extraction tube installed<br>• Insertion tube installed<br>• Sanitizing and filling insertion tube with water<br>• Flow rate ~0.5 ft/s<br>• Conducted inspection (~1-1/2 hr); transmitter in same module as sensors<br>• Above ground tracker briefly lost contact with PipeDiver®; flow stopped to relocate<br>• Removed insertion and extraction tubes<br>• Additional machined defects added |

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[17] A significant rain event occurred on July 22, 2009 that prevented LWC from discharging to the storm sewer for a full day. As such, the inspection vendor was unable to access the pipeline for condition assessment until July 23, 2009.

### Table 3-12. Daily Activities for Each Inline Inspection Technology Vendor (Continued)

| Date | Daily Activities |
|---|---|
| Jul. 28 | • Extraction tube installed (~20 min)<br>• Insertion tube installed (~20 min)<br>• Sanitizing and filling insertion tube with water (~30 min)<br>• Pipe pressure at 52 psi; flow rate ~1 ft/s<br>• Conducted inspection (~35 min)<br>• Removed insertion and extraction tubes |
| Jul. 29 | • Packaged equipment for shipping |
| **NDE Systems See Snake® – 3 operators** | |
| Aug. 31 | • Winch truck arrived |
| Sept. 1 | • Check-in at demonstration site<br>• Retrieved rental winch; steel pull cable installed in line<br>• Foam cleaning pig pulled through test pipe to dewater line (pulled from receive pit to launch pit) |
| Sept. 2 | • Inspection equipment arrived in the evening |
| Sept. 3 | • Check-in at demonstration site and set-up for See Snake® inspection<br>• Set-up winching truck at extraction end of test pipe<br>• Test pull to ~100 ft; lots of background noise recorded<br>• Conducted inspection; pull speed was too fast and cable was not pulling smoothly (~2 ½ hrs); therefore signal/noise ratio on data collected was not acceptable<br>• Pull back cable (~1 ½ hrs) |
| Sept. 4 | • Set-up winching truck at extraction end of test pipe<br>• Conducted inspection; speed ~14.5 ft/min (~2-1/2 hrs)<br>• Pull back cable<br>• Packaged equipment for shipping |

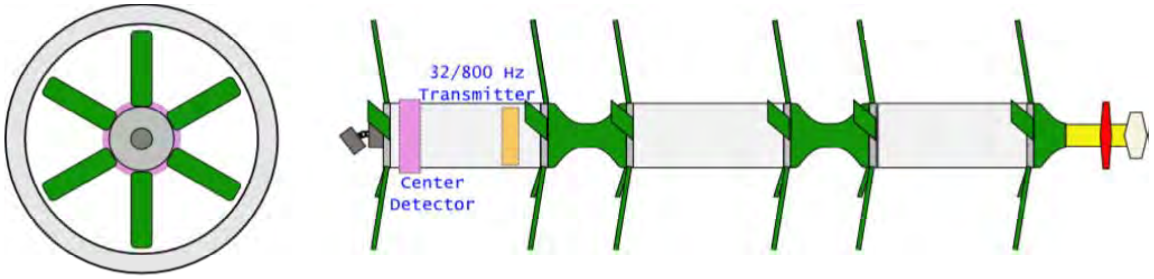
**Sahara Video.** Five Sahara® insertions were performed from July 13 to July 17 for three different inspection technologies (leak detection, video, and condition assessment) that used the same tether, insertion equipment, and tracking method as the leak detection technology. The Sahara® video inspection was performed first on July 13 to inspect the inside of the pipeline. This inspection identified potential obstacles for other internal inspections, as well as internal corrosion and air pockets. The Sahara® video head was inserted into Pit 1 and traversed the line using the pipeline flow. In its initial launch, the Sahara® video parachute caught during insertion and failed to deploy; it was replaced rather than repaired. Once re-inserted, the Sahara® video head traveled the length of the test pipe. After reaching Pit 3, the video head was then retracted and taken out of Pit 1.

**PipeDiver®.** The PipeDiver® RFEC demonstration was performed from July 21 to July 29 with four full runs completed in that timeframe. This demonstration represented a pilot inspection for PipeDiver® using the RFEC technique in metallic pipe. Table 3-13 shows the details of the four inspections, specifically highlighting the survey length, flow speed, and description of the inspection.

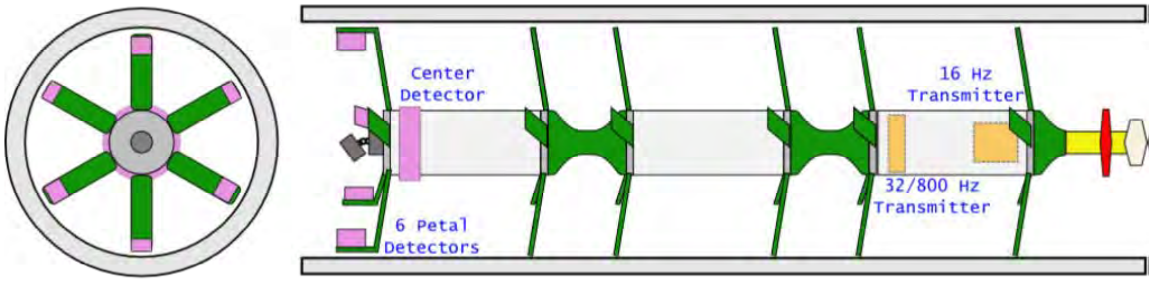
### Table 3-13. PipeDiver® Insertion Details

| Date | Insertion Point | End Point | Survey Length (ft) | Flow Direction and Speed | Description |
|---|---|---|---|---|---|
| July 23 | Pit 1 | Pit 3 | 2,057 | East, 1 ft/s | PipeDiver® RFEC |
| July 24 | Pit 1 | Pit 3 | 2,057 | East, 0.5 ft/s | PipeDiver® RFEC |
| July 27 | Pit 1 | Pit 3 | 2,057 | East, 1 ft/s | PipeDiver® RFEC |
| July 28 | Pit 1 | Pit 3 | 2,057 | East, 1 ft/s | PipeDiver® RFEC |

Many configurations of PipeDiver® were used for the inspection during the demonstration. One was a remote field transformer coupling (RFTC) configuration, which is similar to a method used on prestressed concrete pipe. Another configuration, remote field eddy current, (RFEC) involved moving the exciter coil forward to the first module, and adding six additional detector coils to petals at the rear of the vehicle. A schematic of these two PipeDiver® coil locations is provided in Figure 3-33. Only the results of the tests with the RFEC configuration (bottom illustration in Fig. 3-33) were reported.



Coil Setup for the RFTC Inspection Technique



Coil Setup for the RFEC Inspection Technique

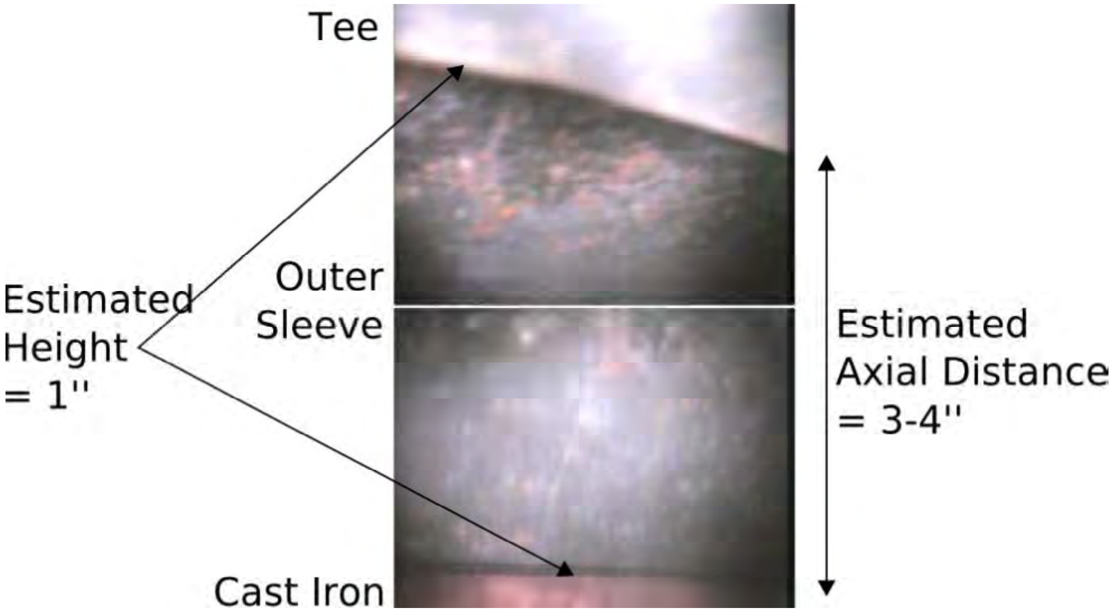
(Courtesy of vendor)

**Figure 3-33. PipeDiver® Coil Locations**

Common factors that affect the accuracy of the PipeDiver® RFEC system include the pipeline design and composition (i.e. metallic variations), inspection tool calibration, inspection tool riding quality, and the type and position of the defect. The future challenges for PipeDiver® RFEC development will be to increase the number of detectors close to the pipe wall to increase the resolution and accuracy for sizing individual pits.

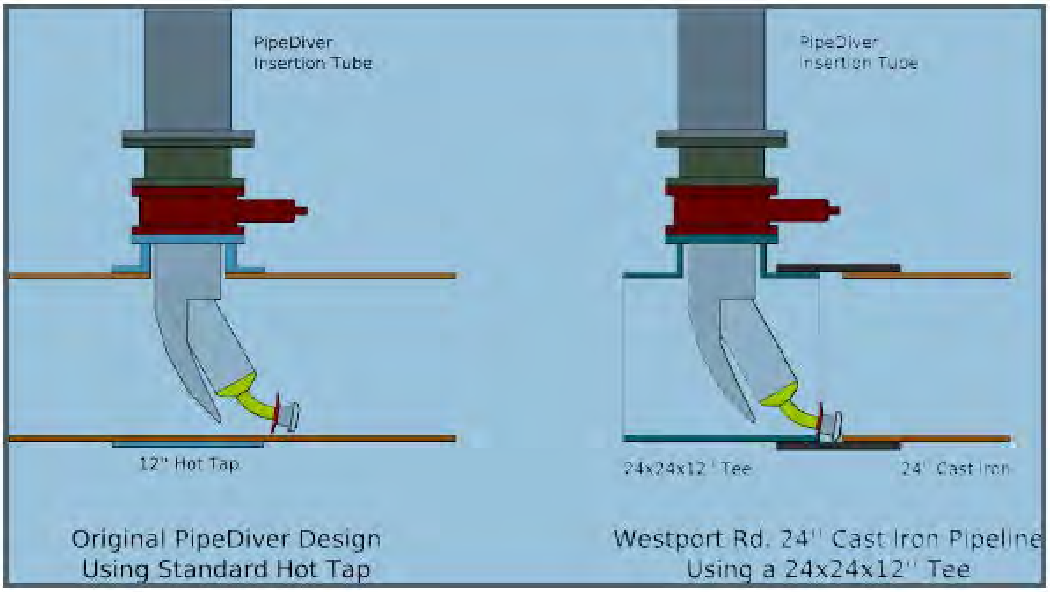
During the first insertion attempt on July 21, 2009, the PipeDiver® vehicle became stuck during the insertion process and therefore the launch had to be aborted. Video data was recorded during the Sahara® Video (Figure 3-34) inspection to investigate what was causing the PipeDiver® vehicle to become stuck in the line. The inspection vendor’s conclusion was that the front of the PipeDiver® vehicle had become stuck in a 3- to 4-in. wide, unfilled gap between joints just downstream of the insertion point (see schematic in Figure 3-35).

Modification of the tool was designed and implemented allowing for the completion of four inspection runs. PipeDiver® is designed for live inspections using standard accesses including 12-in. diameter hot taps, tees with minimum joint gaps, or similar features. For certain accesses such as tees with large unfilled joint gaps or accesses with unknown internal conditions, the vendor recommends using Sahara® Video prior to the inspection to identify the exact layout of the insertion point. The insertion design and process can then be modified for a successful insertion if required.



(Courtesy of vendor)

**Figure 3-34. Sahara® Video of the Joint Gap**



(Courtesy of vendor)

**Figure 3-35. PipeDiver® Insertion Schematic**

**See Snake®.** The water main was available for See Snake® demonstration from August 31 to September 4, the equipment arrived the evening of September 2, and two full runs were completed in that timeframe. This demonstration represented the first live inspection for the custom designed See Snake® tool for a 24-in. diameter cast iron water main.

Prior to the arrival, the line was prepared. An 1/8-in. nylon rope was flowed through the line. Then the isolation valves were closed and 12 ft of pipe was removed from both ends. Since the small nylon line was not strong enough to pull the steel cable, a stronger MULETAPE® line was threaded in the pipe using the 1/8-in. line. The first three days of the demonstration were spent preparing the wire line truck, threading the pipeline with a steel cable to pull the RFT tool back to the launch point, cleaning and dewatering the line using a foam cleaning pig, and preparing the RFT tool for inspection.

On September 3, a test pull was conducted over a 100 ft length of pipe to verify the detectors and data processing systems were working properly. This initial test showed a lot of background noise.

Upon completion of the test pull, the inspection vendor adjusted tool settings and prepared for the live inspection. Unfortunately, because the pulling speed on the cable was too high and the two winches were not synchronized properly, the RFT tool experienced rapid velocity excursions during most of the inspection and therefore the data collected was not usable.

On the last half-day of the demonstration, the inspection vendor completed a smooth inspection run of the entire 2,057 ft length of test pipe at an inspection speed of approximately 14.5 ft/min with the data recorded being of good quality.

The logged distance data for the test pipe was 2,059 ft, with zero set at the 12-in. launch tee. The data from the first three pipe segments were not analyzed by the vendor because of velocity excursions at the start of an inspection .

The complete system used to perform the pipeline inspection included the following equipment:

- 24-in. diameter water pipeline See Snake® RFT tool with data download USB box
- Odometer adaptor box, odometer hydrant adapter, with supporting shoring rod
- Cleaning swab
- Wireline truck with winch fitted with 1 km of wire line
- Laptop running a distance logger
- Proprietary post-analysis software.

Figure 3-36 shows the set-up, with winch truck, hydrant odometer, shoring rod, and spent cleaning swab. The wire line truck is aligned with the launch point to insure the straightest pull possible from the winch to the entry point.

Although EPA’s contractor provided the specifications for several manufactured metal loss defects (calibration defects) to allow calibration of the RFT equipment, the inspection vendor was not able to use the RFT data collected at these locations due to the extremely noisy signals they received. The noise was present in both the September 3rd and September 4th data, pointing to possible magnetic permeability noise within the pipe wall, possibly caused by previous inspections made by magnetic external tools such as ECAT.

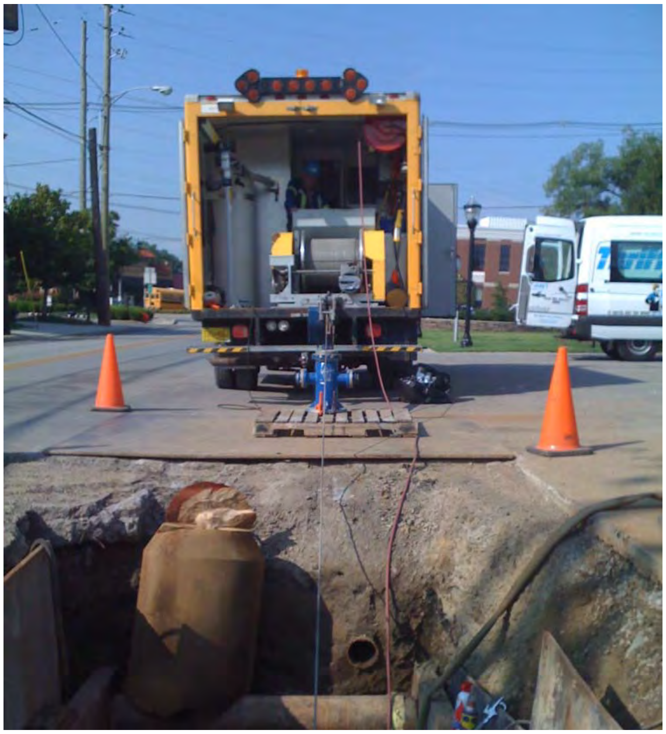


**Figure 3-36.  Wireline Truck and Hydrant Set-up**

In general, the magnetic permeability of a pipe section remains fairly constant over its length; however it is possible for stresses or other external factors to locally change the permeability of the cast iron material.  This is quite unusual, but if present, the RFT tool (which measures magnetic fields far weaker than the earth's magnetic field) would see these changes in the magnetic properties of the pipe.  If the magnetic permeability variations are very strong, they can become "noise" that masks potential defects.

The inspection vendor identified some possible causes for the permeability noise:

1. If the calibration defects were machined with no or little coolant, this could cause stresses in the pipe around the defects and locally change the magnetic permeability.
2. If the machining equipment for the defects employed a magnetic base to clamp the equipment to the pipe, the strong permanent magnets would alter the local permeability significantly.
3. It is also possible that some of the other NDE techniques used permanent magnets for attaching their external scanning devices which would leave large magnetic "imprints".
4. Finally, some of the other NDE techniques may have tried to magnetically saturate the pipes at the defect locations. That process would also leave large magnetic imprints on the pipe.

For optimal RFT accuracy, a calibration is performed using pipe with approximately the same pipe properties (e.g., wall thickness and grade) as the pipe being inspected.  However, in this case the data from the calibration defects was too noisy to be usable.  So instead, the calibration was performed by running the tool through a 24-in. calibration pipe in the inspection vendor's yard after the field demonstration and comparing the data from the cast iron main to data from the yard calibration.  Based on this procedure, the defect accuracy is expected by the inspection vendor to be +/-20% for short (local) wall loss, and +/-10% for long (general) wall loss. The above accuracy range is valid for indications sufficiently removed from major features, such as bell-and-spigot joints. This technology detects bell-and-spigot joints but cannot inspect them at this time.

3.5.3 External Inspection. Two vendors participated in the water main inspection demonstration for external condition assessment tools on the following dates:

- AESL – On site from August 17, 2009 through August 21, 2009
- RSG – On site from August 24, 2009 through August 27, 2009

The activities conducted each day are provided in Table 3-14.

**Table 3-14. Daily Activities for Each External Condition Assessment Technology Vendor**

| Date | Daily Activities |
|---|---|
| **AESL – 2 operators** | |
| Aug. 17 | • Check-in at demonstration site and set-up equipment<br>• Conducted soil analyses and collected samples in Pit F<br>• Conducted wall thickness and coating assessments in Pit F<br>• Started ECAT scan of Pit F |
| Aug. 18 | • Finished ECAT scan of Pit F<br>• Conducted soil analyses and collected samples in Pit L<br>• Conducted wall thickness and coating assessments in Pit L (2-3 hours)<br>• Conducted ECAT scan of Pit L (2-3 hours) |
| Aug. 19 | • Additional soil analysis in Pit L<br>• Conducted soil analyses and collected samples in Pits A, B, C, 1, and 2<br>• Conducted wall thickness and coating assessments in Pit 2 (2-3 hours)<br>• Conducted ECAT scan of Pit 2 (2-3 hours) |
| Aug. 20 | • Conducted soil analyses and collected samples in Pits D, E, and 3<br>• Started cleaning equipment for shipping back to the UK |
| Aug. 21 | • Finished cleaning equipment and packaged for shipping |
| **RSG – 1 operator** | |
| Aug. 24 | • Check-in at demonstration site and set-up equipment<br>• Conducted HSK scan of Pit L (~1-1/2 hour)<br>• Conducted HSK scan of Pit F (~1-1/2 hour) |
| Aug. 25 | • Conducted CAP scans of Pit A, B, C, and D (< 1 hour per keyhole)<br>• Conducted HSK scan of Pit 2 (~1-1/2 hour) |
| Aug. 26 | • Rescanned Pit F |
| Aug. 27 | • Conducted CAP scan of Pit E |

**AESL ECAT.** AESL used a detailed process for assessing the pipeline condition within each excavation location. To start, AESL required the pipe manufacturing specification as input data for their structural analysis. However, due to the age of the pipeline used in the demonstration, this information was not readily available. Instead, AESL used the pattern of wall thickness measurements and pipeline installation date to determine the most appropriate British Standard (BS1211-1945 Class D). The principal structural details provided by this Standard are given in Table 3-15.

Soil measurements including resistivity, redox, pipe-to-soil potential and pH were taken at every accessible excavation along the length of the pipeline (Pit 1, Pit L, Pit 2, Pit 3, Pit A, Pit B, Pit C, Pit D, Pit E, and Pit F). The soil measurement data were used to evaluate the soil corrosivity according to the French Standard AFNOR A05-250.

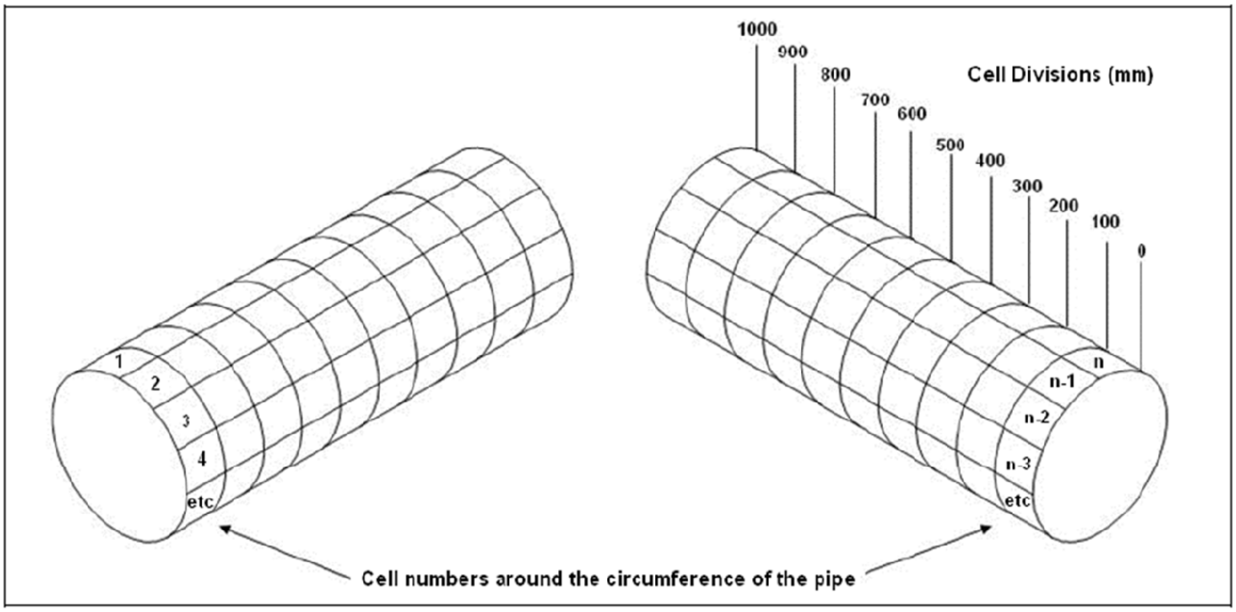
**Table 3-15. Principal Structural Details for Water Main Based on BS1211-1945 Class D**

| Parameter | Data |
|---|---|
| • Nominal Internal Diameter (in.) | 24 |
| • Nominal Wall Thickness (in.) | 0.85 |
| • Maximum Wall Thickness (in.) | 0.89 |
| • Minimum Wall Thickness (in.) | 0.78 |
| • Design Pressure* (psi) from Standard | 175 |
| • Specified Minimum UTS (ksi) from Standard | 28 |
| • Design Stress** (ksi) from Standard | 6.7 |

*Design pressure is calculated as 50% of the specified test pressure
**Design stress is calculated as 25% of the Specified Minimum UTS

The pipe wall thickness was measured using an ultrasonic instrument (Sonatest Sitescan 140), which has a tolerance of 0.01 mm. The ultrasonic gages were calibrated, then ten ultrasonic measurements were taken at every 30-degree pipe orientation for a total of 120 measurements taken at each excavation location (Pit 2, Pit L, and Pit F).

Additionally, a detailed assessment of the pipeline coating and pipe wall was conducted over 1 m long lengths within each excavation location. To quantify the level of coating failure, a similar grid pattern to the ultrasonic wall thickness assessment was used to visually report the percentage of coating failure as depicted in Figure 3-37 with the both sides of the pipe illustrated. The number system shows n circumferential locations; numbered clockwise with respect to the direction of flow, the first cell clockwise from the top of the pipe is 1 and the last one is n.



(Courtesy of AESL)

**Figure 3-37. Pipe Grid Diagram for Visual Coating Assessment**

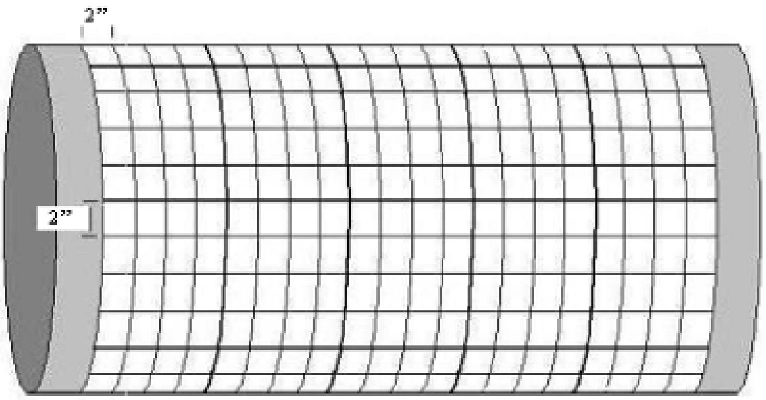
Pipeline integrity was determined via scans with the ECAT. The ECAT technology is applicable for ferrous pipes, including cast iron, ductile iron, and steel. The ECAT used in the demonstration was 1.6 m long and contained four sensor blocks each with a hall-effect sensor to measure the volume of metal loss and a proximity sensor to denote if the metal loss is internal or external. Each individual scan took approximately 3 minutes with a total duration of two to three hours for full circumferential inspection of a 1 m long segment of pipe. The number of sensor blocks and scan rate will change based on the diameter of the pipeline.

The real-time data that is reported shows a series of peaks from the two types of sensors. If the peak from the Hall-effect sensor and proximity sensor align, this type of signal indicates that the metal loss is external. If only one peak from the Hall-effect sensor is registered without a peak from the proximity sensor, this type of signal indicates that the metal loss is internal. The shape of the peak allows the analysts to estimate the size of the defect.

Data from the relative soil corrosivity assessment, pipe coating condition assessment, wall thickness measurements, and full circumference ECAT scans were integrated and analyzed to determine the pipe condition in the three excavated pits. Subsequent statistical analyses were conducted to predict the condition of the un-inspected portions of the pipeline based on the detailed findings within the excavated pits.

**RSG HSK.** The HSK system used for the demonstration uses electromagnetic energy to produce images that are used to infer the thickness of the pipe material. The HSK approach involves one operator to place the antenna on the pipe surface, normally in an excavation pit and ideally with an accurate reference system. The operator moves the antenna around the circumference of the pipe, and then along the pipe length to acquire the pipe condition data. Full pipe coverage (100%) is typically achieved using the HSK method, apart from where obstacles are encountered, such as valves and joints. Where joint scans are required, these need to be done separately to the pipe sections. The acquired data is typically stored on a laptop located outside of the excavation pit.

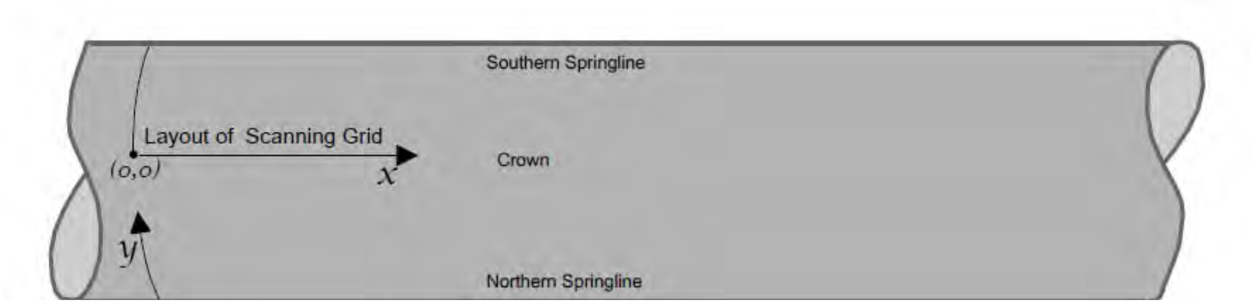
The most preferred procedure is to use pre-plotted grid paper with 2-in. intervals, taking individual readings around the circumference. The paper is wrapped around the outside of the pipe allowing for accurate reference points of each individual reading taken. The evaluation grid with survey orientation is schematically illustrated in Figure 3-38. Scanning is conducted from the outside of the pipe along the circumference starting and finishing at the crown of the pipe.



(Courtesy of RSG)

**Figure 3-38. Typical Survey Grid Along a Pipe Section**

For this demonstration, chalk and tape were used to mark a reference grid on the pipes external surface rather than the pre-plotted grid paper. All HSK scans for this project started at the crown of the pipe, moving around the circumference and finishing back at the crown of the pipe (see Figure 3-39).



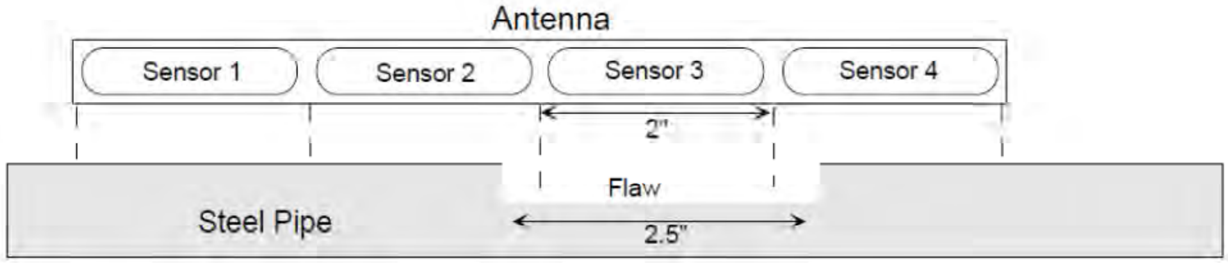
(Courtesy of RSG)

**Figure 3-39. Plan View of Specific Referencing for Pipe Section Survey**

Interpretation of the BEM HSK data is based on an established relationship between recorded signal and thickness measurement. With accurate calibration information, a correlation between signal amplitude and pipe wall thickness can be obtained. However, RSG mentions in their report that microstructures within ferrous materials make it impossible to determine an absolute thickness conversion. In addition, the signal is averaged over an area and volume scanned by the sensors (for this demonstration approximately 2x2-in.), which make absolute measurements of wall thickness difficult. Therefore, only relative or apparent thickness correlations are provided in the results. Various sensor sizes are available allowing more detailed assessments or faster surface coverage. The selection of the sensor can be tailored to suit the required detection and/or budget.

Since the sensors average over a 2x2-in. area, the corrosion within the area is reported as average metal loss in the scan area, not the deepest depth. For this reason, isolated pits that are small in diameter or surface scratches (unless significantly large with respect to the scanned area) will not be seen as significant and may not have enough impact to affect a particular reading. In addition, the HSK system is not able to discern if the metal loss is internal, external, or both and will indicate a cluster of pits as general wall thinning.

According to RSG, the BEM plots generated by the HSK are a good representation of the area of each flaw and flaw trends. However, understanding the nature of the HSK operation and antenna orientation with respect to the flaw is crucial in determining size of flaws. A common situation is that a low response from a certain number of sensors does not equate to a flaw of that size (see Figure 3-40). For example, a low response captured from three 2-in. sensors does not necessarily equate to a flaw 6-in. in size. Similarly, a flaw small in area (< 2 in$^2$) may be scanned by up to four different sensors, resulting in a thickness contour plot indicating a larger flaw area of lesser wall thinning than actual.

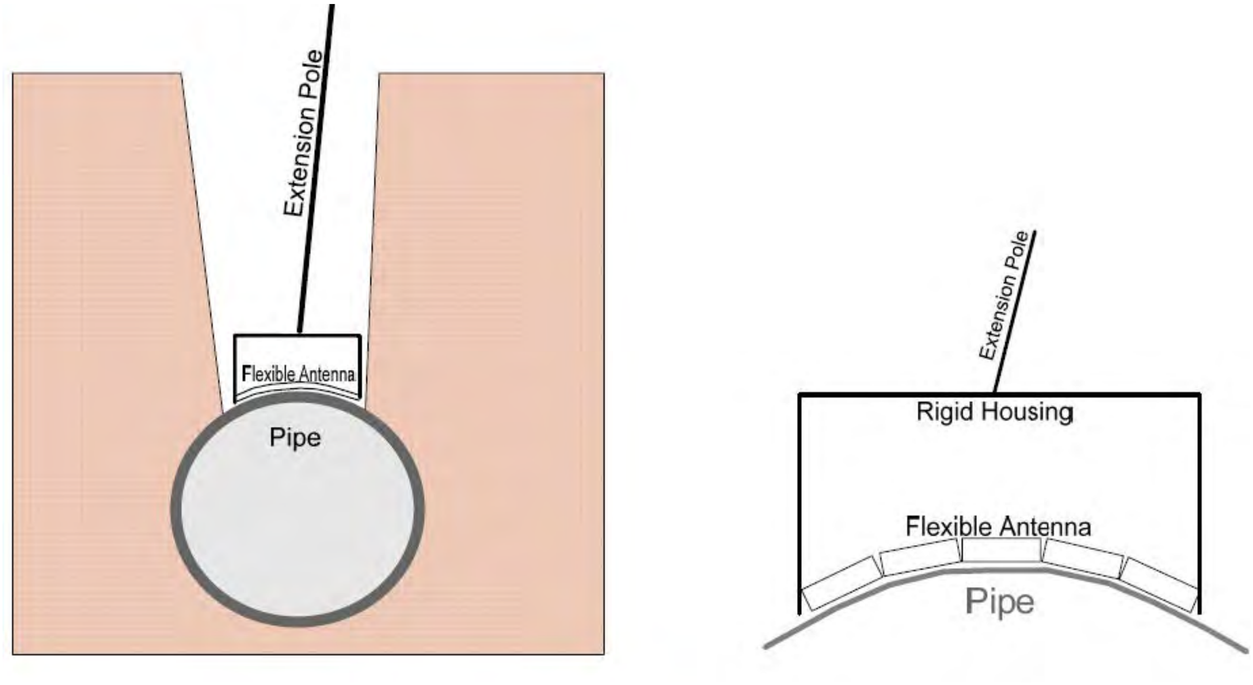


(Courtesy of RSG)

**Figure 3-40. Representation of Sensors Responding to Flaw**

**RSG CAP.** The CAP system uses the same BEM technology as previously discussed for the HSK. The CAP approach, however, does not require manned entry into the excavation pit. Instead, access to the pipe is gained through smaller, vacuum excavations near the crown of the pipe. As such, only the area excavated is available for scanning and assessment. CAP scans do not provide a detailed assessment of the 'full' circumference of the pipe, but it allows for quicker sampling of many locations along the pipe length. Full circumference scanning capability is now reported to be available.

The CAP system is ideally suited for situations where corrosion occurs or is suspected to occur along the crown of a pipe. Trends in pipe crown corrosion will only be identified along the length of the pipeline if a suitable number of CAP scans are performed. Antennae are lowered into the vacuum excavated hole (keyhole) on an extension pole and pressed firmly to the crown of the pipe to allow for good contact between the antenna and pipe. The housing of the antennae is made of flexible material such as cotton to allow the antenna to conform to the curvature of the pipe as shown in Figure 3-41. Interpretation of the BEM CAP data is essentially the same as the HSK system except that the area scanned by the sensors is approximately 1x1-in. rather than 2x2-in. Similar to the HSK, various sensor sizes are available allowing more detailed assessments or faster surface coverage.



(Courtesy of RSG)

**Figure 3-41. Typical CAP Scan Set-up and Design**

# 4.0: MATERIALS AND METHODS FOR POST-DEMONSTRATION CONFIRMATION STUDY

A post-demonstration confirmation study was conducted in order to select, characterize, and compare the condition of exhumed pipe samples to the pipe inspection data that was collected by the inspection technology vendors during the field demonstration in Louisville, KY. The confirmation study included an assessment of the "as new" wall thickness, inside cement coating thickness, and pipe outer diameter (OD) measurements for 12 exhumed pipes. The exhumed pipes were also assessed manually and/or with a laser scanner in order to determine the extent of metal loss. The extent of metal loss was characterized by total volume loss, number of pits (with loss greater than 50% of depth), maximum pit depth, and largest corrosion patch dimensions. This section presents the rationale for selection of the exhumed pipe segments and the methodologies used for the pipe condition assessment during the post-demonstration confirmation study. Additional information can be found in Appendix A, which includes photo documentation of the exhumed pipes before and after sandblasting, along with the manual and laser scanning assessment data.

The section describes data collection, analyses, and project documentation associated with the post-demonstration confirmation study performed under TO 62 in accordance with EPA NRMRL's Quality Assurance Project Plan (QAPP) Requirements for Applied Research Projects (EPA, 2008). In performing the work, Battelle followed the technical and QA/QC procedures specified in the QAPP unless otherwise stated. Any procedure that was not followed and the rationale for the change is noted in the remaining sections.

## 4.1 Selection of Pipe Segments for Removal

After the field demonstration was complete, a CCTV inspection of the entire test pipe length was performed using PipeEye CCTV. The inspection report indicated that the cement liner was uniform and no through-wall anomalies were detected in the pipe wall. The joints at the reported natural leak locations were closely examined, as well as the joints before and after these leak locations, and no significant differences (such as larger gaps) were observed. Upon completion of the CCTV and joint evaluations, the 24-in. diameter test pipe was removed by LWC to prepare for installation of the 30-in. diameter replacement line. As the 24-in. line was being removed, EPA's contractor was on site to select over 200 ft of pipe for post-demonstration confirmation of the condition assessment technology results. Pipe segments were selected using the inspection results reported by each technology vendor and visual assessment of the pipe condition as it was removed. The selected pipe segments were taken to a holding area for storage and then transported to the EPA contractor's laboratory.

Selection of the pipe segments used for post-demonstration verification was based on input from each technology vendor and the EPA contractor's review. Pipes with reported anomalies, as well as those thought to be in good condition were selected. Approximately 220 ft of pipe were identified as potential candidates for further assessment based upon inspection results and visual examination during excavation. This included:

- 17 entire pipe segments with bell and spigot intact
- Two 12-in. tees used for launching and receiving condition assessment equipment
- One 6 ft section with:
    - Machined anomalies, and
    - Through holes from corp valve taps used to simulate leaks.

Table 4-1 provides a consolidated list of the pipe segments removed for post-demonstration verification. The criteria used to select the pipe segments included pipes identified as anomalous by multiple vendors, pipes identified as 'good' by multiple vendors, and individual vendor interest in specific pipe segments for evaluation.

Initially, this selection did not include pipe selections from the results of See Snake® as they were the last vendor to participate in the demonstration and their final report was not available at the time that the pipe segments were selected and removed. However, Russell NDE Systems Inc. was given the opportunity to select an additional few pipe segments (No. 61, 65, and 68) for post-demonstration verification based on their preliminary results.

The pipes were marked for removal by placing a nail and colored washer at the estimated 'middle' of the selected pipe segments. Then as the pipes were being removed by MAC Construction during installation of the 30 in. water main, the joints adjacent to the nail were carefully removed, marked with the sequential pipe number, and saved for shipping to EPA contractor's laboratory.

The excavated pipe segments were in generally good condition and structurally sound. The internal cement liner was visually examined and no obvious anomalies were detected. The exterior of the pipe was also examined and appeared to be in its original state with limited, localized graphitization and corrosion detectable. As each pipe length was removed from the ground, it was sequentially numbered and the top of the pipe was marked with spray paint.

## 4.2 Selection of Pipe Segments for Post-Demonstration Wall Thickness Assessment

Twelve pipe lengths were selected, from the over 200 ft of pipe removed, for full wall thickness assessment. Because the external assessment methods focused their assessments on specific pit locations, four specific pipe lengths were selected for these technologies. The other eight pipe segments were selected to demonstrate the assessment capability of the acoustic wall assessment and internal inspection technologies that assessed the entire pipe segment.

Few obvious signs of significant pipe degradation were found on site. The pipe had a relatively uniform visual appearance. Tapping with a sharp tool (solid metal sounds bright) did not expose significant graphitization; this was not uniformly applied as pipe was removed quickly. Therefore, pipe selection relied upon inspection data from all of the condition assessment vendors and included regions with suspected anomalies and pipe segments that were thought to be in good condition.

After the pipes were removed, they were sequentially numbered and the top of each pipe was marked. Table 4-2 provides the pipe length number, approximate location of the bell and spigot joint, and reason for selection for the twelve exhumed pipes.

Table 4-1. Consolidated List of Pipe Sections Removed for Post-Demonstration Verification

| Est. Start | Est. End | Nail | Joint # | Comment | Length (ft) | Depth to Top (in.) |
|---|---|---|---|---|---|---|
| 0 | 8 | **-** | 1 | Pit 1. Tee remove to assess | 8.375 | - |
| 327 | 339 | **333** | 29 | Pit L. Leaks found by all technologies. Pipe segment immediately before sewer. | 12 | 71.5 |
| 339 | 351 | **345** | 30 | Pipe segment immediately after sewer. Sahara® and PipeDiver® indicated anomalies | 12 | 70.5 |
| 351 | 363 | **357** | 31 | If MAC can't get the joint immediately after sewer, this is an alternative in the wet area. Sahara® and PipeDiver® indicated anomalies | 12 | 68 |
| 567 | 579 | **573** | 49 | Pit 4: 574-580 ft; Valve = 577.4 ft surface, 583 ft Pipe Eyes. Pure low velocity 560 ft to 583 ft (first choice). See Snake® 5 pits. | 12 | - |
| 651 | 663 | **657** | 56 | Pure requested pipe segment 1. See Snake® 4 pits. | 12 | - |
| 663 | 675 | **669** | 57 | Pure requested pipe segment 2. | 12 | - |
| 711 | 723 | **717** | 61 | See Snake® saw 2 50% pits; Pure low velocity. | 12 | N/A |
| 723 | 735 | **729** | 62 | Pure low velocity (2nd choice) | 12 | - |
| 735 | 747 | **-** | 63 | Additional pipe selected during site visit; See Snake® 4 pits. Pure low velocity. Graphitization & mechanical damage found | 12 | N/A |
| 747 | 759 | **-** | 64 | Pure low velocity; See Snake® 5 pits. | 12 | N/A |
| 759 | 771 | **765** | 65 | See Snake® requested pipe 756-768 ft. Pure low velocity | 12 | N/A |
| 771 | 783 | **-** | 66 | Tapping sound variation indicated graphitization may be present. See Snake® 7 pits. Pure low velocity. | 12 | N/A |
| 783 | 795 | **-** | 67 | Tapping sound variation indicated graphitization may be present. See Snake® 8 pits. | 12 | N/A |
| 795 | 807 | **801** | 68 | See Snake® requested pipe. 793 - 805 ft | 12 | N/A |
| 807 | 819 | **813** | 69 | Pit C: 809-815ft - RSG; corrosion & graphitization | 12 | - |
| 1,078 | 1,090 | **-** | 91 | Pit 2: 1,080-1,090 ft | 12 | - |
| 1,162 | 1,174 | **1,168** | 98 | Pit D: RSG keyhole reference (good pipe). See Snake® no anomalies. | 12 | - |
| 1,630 | 1,642 | **1,636** | 137 | Internal anomaly at 1,637 ft with Sahara® Video. PipeDiver® anomalies. Sahara® WTT 3rd choice. | 12 | - |
| 1,726 | 1,738 | **-** | 145 | Pit F: RSG and AESL. | 9.4 | - |
| 1,738 | 1,750 | **-** | 146 | Pit F: RSG and AESL. Sahara® WTT and PipeDiver® anomalies | 5.5 | - |
| 1,906 | 1,918 | **1,912** | 159 | Leak, Sahara® WTT and PipeDiver® anomalies. | 12 | - |
| 1,978 | 1,990 | **1,984** | 166 | PipeDiver® reference (good pipe). See Snake® no anomalies | 12 | - |
| 2,050 | 2,062 | **-** | 172 | Pit 3: 2,055-2,063 ft | 5.375 | - |

**Table 4-2. Pipes Selected for Full Assessment during Post-Demonstration Verification**

| Pipe Length #| Bell location (Ft) | Spigot Location (Ft) | Reason for Selection |
|---|---|---|---|
| 30 | 339 | 351 | Pit L. Large leak at the spigot of pipe segment 30 / bell of pipe segment 31. PipeDiver® indicated anomalous pipe. Sahara® WTT indicated a medium change in wall thickness. ECAT and HSK external pipe inspection indicated anomalous pipe. |
| 32 | 363 | 375 | Pipe segment 31 was the first choice, but could not be extracted intact from under the sewer line. This area was wet from a large leak and degradation was expected. Pipe Diver indicated anomalous pipe. Sahara® WTT indicated a medium change in wall thickness. |
| 49 | 567 | 579 | SmartBall™ PWA detected low velocity and recommended pipe segment for excavation. |
| 56 | 651 | 663 | SmartBall™ PWA indicated normal pipe wall condition and recommended pipe segment for excavation. |
| 61 | 711 | 723 | See Snake® inspection reported wall loss anomalies. PWA detected low velocity and recommended pipe segment for excavation. |
| 63 | 735 | 747 | See Snake® inspection reported a large number of wall loss anomalies. |
| 64 | 747 | 759 | See Snake® inspection reported wall loss anomalies. PWA detected low velocity |
| 69 | 807 | 819 | Pit C. Corrosion documented by RSG CAP and verified in the field |
| 98 | 1,162 | 1,178 | Pit D. Pipe Diver indicated anomalous pipe. RSG CAP reported as moderate corrosion at crown of the pipe |
| 137 | 1,438 | 1,450 | Pipe Diver indicated anomalous pipe. Sahara® Video indicated anomalies and air pocket |
| 145/146 | 1,728 | 1,750 | AESL ECAT and RSG HSK external pipe inspection. |
| 166 | 1,978 | 1,990 | Good pipe sample requested for verification by PipeDiver® and Sahara®. |

## 4.3 Transportation, Storage, and Surface Preparation

After removal, the selected pipe segments were placed in a holding area at the construction site in Louisville, KY. In November 2009, the pipe lengths were trucked to the EPA contractor's pipeline testing facility in West Jefferson, Ohio. Post-demonstration assessment was conducted in the Fall of 2010 when the post-confirmation study scope was funded. All of the pipes were photographed before and after sandblasting. The pipes were professionally sandblasted by Martin Painting and Coating Company in Columbus, OH to remove the enamel coating, corrosion products, and graphitization to facilitate assessment of the pipe degradation.

Three standard levels of blasting, described in Table 4-3, were available and assessed. Initially, the pipe was blasted to a NACE-3 Commercial Blast Cleaning finish. A visual inspection revealed that not all of the corrosion and graphitization were removed. A 3-ft-square area with metal loss and un-corroded pipe wall was blasted to a NACE-2 Near-White Blast Cleaning finish. Nearly all of the corrosion and graphitization was removed, though sharp features remained at the edges of corrosion pits. A ½-ft-square area with sharp pits and small amounts of remaining corrosion and graphitization was blasted to a NACE-3 White-Metal Blast Cleaning finish. While all of the corrosion and graphitization appeared to be removed, the sharp features that remained at the edges of corrosion pits were dull and the pit sizes appeared to be expanded. The NACE-1 blast procedure was considered to be too aggressive and therefore all pipes were blasted to a NACE-2 Near-White Blast Cleaning finish and lightly primed to prevent additional corrosion. After blasting and priming, the pipe identification numbers and orientation markings were transferred back to each pipe segment for identification and orientation.

**Table 4-3. Blast Finish Considered for Preparation of Pipe for Assessment**

| NACE[a] | SSPC[b] | Method Name | Method Description |
|---|---|---|---|
| 1 | SP-5 | White Metal Blast Cleaning | The surface shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter to the unaided eye. |
| 2 | SP-10 | Near-White Blast Cleaning | The surface shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter of at least 95% of each unit area |
| 3 | SP-6 | Commercial Blast Cleaning | The surface shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter over at least two-thirds of each unit area. |

[a] Standard identifier of NACE International, originally known as the National Association of Corrosion Engineers. A consensus standard with SSPC.

[b] Standard identifier of the Society for Protective Coatings, originally known as Steel Structures Painting Council. A consensus standard with NACE.

## 4.4 General Pipe Parameter Measurements

The original construction records show that cast iron pipe was most likely spun cast using the De Levaud process. This section reports on the original wall thickness, inside cement coating thickness, and OD measurements.

**Wall Thickness Measurements.** The wall thickness of the cast iron pipe is the key parameter that defines the pressure-carrying capability of the pipe. Two methods are available for assessing wall thickness of the cast material as follows:

- Caliper for pipe where ID and OD of the cast iron pipe are accessible and can be spanned
- Ultrasonic measurements on areas of the pipe where only one side is accessible.

**Caliper Measurements**. At the spigot or where the pipe has been cut, the thickness of the cast iron pipe was measured with a caliper. The caliper was calibrated by EPA contractor's instrumentation services group. Measurements were taken at four locations around the pipe, as close to 90-degrees as possible where the spigot was not corroded: top, right, bottom, and left, defined as viewed from the spigot end. In two cases, measurements were not possible due to localized corrosion. The results were recorded in tabular format as shown in Table 4-4, where the largest and smallest wall thicknesses are noted. For the pipes assessed, the average wall thickness at the spigot was 0.795-in. with a standard deviation of 0.021-in., or 2.5% of the wall thickness. The thickness was uniform around the pipe circumference and most of the deviations were less than 1% of the wall thickness. Some of the larger deviations could have been due either to loss of metal or to the pipe manufacturing process. In general, the pipe wall thickness at the spigot was approximately the same around the circumference, indicating that the pipe is spun cast iron, however, corrosion and damage were observed at many places. Measurements were planned, as detailed in the QAPP, at four locations on the pipe, 0°, 90°, 180°, and 270°. The QAPP procedure was modified to collect caliper measurement in full wall thickness pipe as close to the planned location as possible away from the corrosion and damage at the top, right, bottom and left side of the pipe. The specific locations are contained in the tables in Appendix A. Corrosion and damage were extensive in some areas and caliper measurements could not be made in these quadrants; in the tables these areas are marked with an "x."

**Table 4-4. Spigot Wall Thickness as Measured by a Caliper at Four Locations**

| Pipe Number | Wall Thickness (in.) | | | | Average (in.) | Standard Deviation (in.) |
|---|---|---|---|---|---|---|
| | Top | Right | Bottom | Left | | |
| **30** | 0.781 | 0.784 | 0.79 | 0.776 | 0.783 | 0.006 |
| **32** | 0.806 | 0.803 | 0.805 | 0.796 | 0.803 | 0.005 |
| **49** | 0.782 | 0.786 | 0.806 | 0.798 | 0.793 | 0.011 |
| **56** | x | 0.802 | 0.794 | 0.795 | 0.797 | 0.004 |
| **61** | 0.803 | 0.779 | 0.784 | 0.789 | 0.789 | 0.010 |
| **63** | 0.813 | 0.818 | 0.816 | 0.813 | 0.815 | 0.002 |
| **64** | 0.801 | 0.793 | 0.7965 | 0.797 | 0.797 | 0.003 |
| **69** | 0.776 | 0.774 | 0.742 | 0.742 | 0.759 | 0.019 |
| **98** | 0.814 | 0.799 | 0.812 | 0.84 | 0.816 | 0.017 |
| **137 (Min)** | 0.765 | x | 0.765 | 0.773 | 0.768 | 0.005 |
| **145** | 0.789 | 0.782 | 0.784 | 0.787 | 0.786 | 0.003 |
| **166 (Max)** | 0.829 | 0.834 | 0.833 | 0.842 | 0.835 | 0.005 |
| **Average** | 0.796 | 0.796 | 0.794 | 0.796 | 0.795 | 0.001 |
| **Std Dev** | 0.019 | 0.018 | 0.024 | 0.028 | 0.021 | - |
| **Dev in %T** | 2.4% | 2.3% | 3.0% | 3.5% | 2.6% | - |

x indicates an area where reading could not be acquired.

**Ultrasonic Measurements**. For other areas of the pipe where only the outside was accessible, ultrasonic methods were used. While reasonably precise for fine-grained steels, ultrasonic thickness methods are often less accurate for cast iron pipes because of the potentially larger grain structure. The variation is anecdotally reported to be as much as 20% of the wall thickness (0.150-in.). Spatial averaging methods were used to estimate wall thickness; nine measurements were averaged over a 3×3-in. grid with each cell being ½×½-in. The Olympus Model 37DLP ultrasonic thickness gauge was used as a nondestructive means of measuring pipe wall thickness. The instrument was factory-calibrated at the time of testing. Table 4-5 shows representative ultrasonic wall thickness measurements for three pipe samples. Appendix A contains the results for all of the pipe samples. These results show that the pipes did not exhibit the level of variation often seen in cast iron pipe. The nine readings had a standard deviation between 0.004-in. and 0.013-in. for all pipes. The pipes tended to be slightly thicker at the bell than at the spigot. A summary of the ultrasonic thickness measurements are shown in Table 4-6.

### Table 4-5. Spatial Averaging Methods Were Used to Estimate Wall Thickness

| Pipe Number | Wall Thickness (in.) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| | Caliper | UT | | | UT | | | UT | | |
| **30** | 0.766 | 0.782 | 0.779 | 0.799 | 0.75 | 0.754 | 0.75 | 0.805 | 0.831 | 0.807 |
| | 0.766 | 0.771 | 0.771 | 0.768 | 0.73 | 0.743 | 0.752 | 0.809 | 0.807 | 0.799 |
| | 0.78 | 0.769 | 0.797 | 0.785 | 0.75 | 0.758 | 0.753 | 0.793 | 0.812 | 0.809 |
| **Average** | 0.771 | 0.780 | | | 0.749 | | | 0.808 | | |
| **Standard Deviation** | 0.008 | 0.012 | | | 0.008 | | | 0.010 | | |
| **64** | 0.782 | 0.776 | 0.765 | 0.766 | 0.797 | 0.776 | 0.774 | 0.796 | 0.815 | x |
| | 0.784 | 0.771 | 0.777 | 0.765 | 0.765 | 0.771 | 0.790 | 0.810 | 0.806 | x |
| | 0.788 | 0.762 | 0.759 | 0.766 | 0.775 | 0.766 | 0.771 | x | x | 0.807 |
| **Average** | 0.785 | 0.767 | | | 0.776 | | | 0.807 | | |
| **Standard Deviation** | 0.003 | 0.006 | | | 0.011 | | | 0.007 | | |
| **137** | 0.764 | 0.749 | 0.741 | 0.73 | 0.738 | 0.736 | 0.74 | 0.766 | 0.766 | 0.757 |
| | 0.782 | 0.730 | 0.748 | 0.737 | 0.741 | 0.740 | 0.735 | x | 0.776 | 0.760 |
| | 0.764 | 0.752 | 0.731 | 0.730 | 0.741 | 0.734 | 0.742 | x | 0.785 | 0.786 |
| **Average** | 0.770 | 0.739 | | | 0.739 | | | 0.771 | | |
| **Standard Deviation** | 0.010 | 0.009 | | | 0.003 | | | 0.012 | | |
| x indicates an area where reading could not be acquired. | | | | | | | | | | |

### Table 4-6. Wall Thickness Measurements of Cast Iron Using an Ultrasonic Thickness Gauge

| Pipe Number | Average Wall thickness (in.) | | | |
|---|---|---|---|---|
| | Spigot | | Center | Bell |
| | Caliper | Ultrasonic | Ultrasonic | Ultrasonic |
| **30** | 0.771 | 0.780 | 0.749 | 0.808 |
| **32** | 0.811 | 0.782 | 0.776 | 0.817 |
| **49** | 0.789 | 0.795 | 0.784 | 0.754 |
| **56** | 0.811 | 0.769 | 0.796 | 0.754 |
| **61** | 0.776 | 0.775 | 0.819 | 0.787 |
| **63** | 0.818 | 0.786 | 0.766 | 0.794 |
| **64** | 0.785 | 0.767 | 0.776 | 0.807 |
| **69** | 0.753 | 0.767 | 0.736 | 0.785 |
| **98** | 0.831 | 0.825 | 0.790 | 0.819 |
| **137** | 0.770 | 0.739 | 0.739 | 0.771 |
| **145** | 0.790 | 0.763 | 0.804 | 0.763 |
| **166** | 0.833 | 0.817 | 0.829 | 0.790 |
| **Average** | 0.795 | 0.780 | 0.780 | 0.787 |
| **Deviation** | 0.026 | 0.024 | 0.030 | 0.023 |
| **Dev in %T** | 3.2% | 3.0% | 3.7% | 2.9% |

**Cement Liner Thickness Measurements**. For the ends of the pipes where the cement liner was exposed, such as the spigot or where the pipe was cut, the thickness of the cement liner was measured with the same caliper as used for the cast iron pipe material. Measurements were taken at four equally spaced locations around the pipe using a two-step process. First, the thickness of the pipe and the liner was measured. Second, after a small amount of the liner was removed to expose the pipe internal surface, the pipe thickness was measured and the liner thickness was determined by subtracting the pipe thickness from the total thickness. Table 4-7 shows a representative liner thickness calculation for Pipe 30. Appendix A contains the results for all of the pipe samples that underwent full assessment. The results show that the pipes did not exhibit the level of variation often seen in cast iron pipe; the nine readings had a standard deviation between 0.004 and 0.013 in. for all of the pipes. The liner thickness results for all pipe samples are shown in Table 4-8 with the right and left defined as viewed from the spigot end. The thickness of the liner was, on average, a quarter inch (0.25-in.) and varied from 0.14- to 0.34-in. The liner at a few ends was damaged to an extent that prevented measurement. This most likely occurred during excavation, shipping, or blasting because the video assessment of the pipe interior did not show any damage.

**Table 4-7. Calculation of Thickness of Cement Liner at Spigot with Caliper for Pipe 30**

| Measurement (in.) | Top | Right | Bottom | Left |
|---|---|---|---|---|
| Cast Iron | 0.781 | 0.784 | 0.790 | 0.776 |
| Cast Iron & Cement Liner | 1.113 | 0.953 | 0.933 | 0.982 |
| Cement Liner | 0.332 | 0.169 | 0.143 | 0.206 |

**Table 4-8. Thickness Measurements of Cement Liner at Spigot for All Pipe Samples**

| Pipe Number | Liner Thickness (in.) | | | |
|---|---|---|---|---|
| | Top | Right | Bottom | Left |
| **30** | 0.33 | 0.17 | 0.14 | 0.21 |
| **32** | 0.29 | 0.25 | 0.33 | 0.31 |
| **49** | 0.19 | 0.18 | 0.17 | 0.17 |
| **56** | x | 0.19 | 0.20 | 0.20 |
| **61** | 0.30 | 0.31 | 0.25 | 0.30 |
| **63** | 0.27 | 0.25 | 0.28 | 0.34 |
| **64** | 0.30 | 0.31 | 0.16 | 0.28 |
| **69** | 0.18 | 0.21 | 0.26 | 0.26 |
| **98** | 0.29 | 0.31 | 0.27 | 0.24 |
| **137** | 0.18 | x | 0.15 | 0.16 |
| **145** | 0.32 | 0.32 | 0.31 | 0.31 |
| **166** | 0.32 | 0.24 | 0.22 | 0.17 |
| **Max** | 0.33 | 0.32 | 0.33 | 0.34 |
| **Min** | 0.18 | 0.17 | 0.14 | 0.16 |
| **Average** | 0.27 | 0.25 | 0.23 | 0.24 |
| **Std Dev** | 0.06 | 0.06 | 0.06 | 0.06 |

**Pipe Outer Diameter Measurements**. The average outer diameter of the pipe was measured using a pi tape measure (a measuring tape method that accurately measures diameter using the pipe's circumference). The pi tape manufacturer's procedure was followed.[18] Measurements were made approximately a foot from each end and at the center of the pipe; the results are contained in Table 4-9. The manufacturer states an accuracy of ±0.001-in. However, this is difficult to achieve on pipe pulled from service and an accuracy of ±0.010-in. is more practical. The average pipe diameter was 25.82-in. with a standard deviation of 0.03-in.

**Table 4-9. Outer Diameter Measurements Using a Pi Tape**

| Pipe Number | Pipe Diameter (in.) | | |
|---|---|---|---|
| | Spigot | Center | Bell |
| **30** | 25.84 | 25.81 | 25.82 |
| **32** | 25.83 | 25.87 | 25.83 |
| **49** | 25.84 | 25.84 | 25.81 |
| **56** | 25.82 | 25.79 | 25.81 |
| **61** | 25.85 | 25.83 | 25.84 |
| **63** | 25.80 | 25.78 | 25.78 |
| **64** | 25.83 | 25.88 | 25.86 |
| **69** | 25.88 | 25.81 | 25.86 |
| **98** | 25.88 | 25.80 | 25.76 |
| **137** | 25.80 | 25.80 | 25.81 |
| **145** | 25.83 | 25.80 | 25.80 |
| **166** | 25.90 | 25.80 | 25.79 |
| **Max** | 25.90 | 25.88 | 25.86 |
| **Min** | 25.80 | 25.78 | 25.76 |
| **Average** | 25.84 | 25.82 | 25.81 |
| **Std Dev** | 0.03 | 0.03 | 0.03 |

## 4.5 Assessment of Metal Loss Regions

The amount of remaining metal is a primary measurement for assessing pipe condition. For the pipe segments selected for verification, corrosion and graphitization occurred in patches and the average metal loss areas were measured over larger regions. To identify areas on the pipe, anomalous regions were labeled with a five-part three-digit code, PPP-LLL-AAA-DLL-DAA:

- PPP indicates the pipe number.
- LLL indicates the start location of the defect area along the pipe axis measured from the spigot in inches (values from 0 to 150).
- AAA indicates the start angle of the defect area around the circumference measured from a reference mark indicating top of pipe in degrees (values from 0 to 359). The top of the pipe was marked in the ditch prior to removal.

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[18] http://www.pitape.com/specs/Instructions%20O.D.%20Inch%20Tape.pdf

- DLL indicates the length of the defect area along the pipe axis in inches (values from 0 to 999).
- DAA indicates the circumferential extent of the defect area around the circumference in degrees (values from 0 to 359).

For an area to be identified as an anomalous region, the axial length and circumferential extent of its imperfection had to be greater than one wall thickness (0.75-in.) and the depth of the imperfection had to be greater than 10% of the wall thickness (0.075-in.). Multiple pits were combined into an anomalous region until the distance between anomalous regions was greater than one wall thickness. In this study, standard tape measures were used to locate the anomalous regions. The spigot end of the pipe is defined as the start zero length. Typically, there were between three and five regions per pipe sample.

**Manual Assessment of Wall Loss.** For areas with corrosion and graphitization, the remaining metal was calculated by subtracting the anomaly depth from the local wall thickness. The depth of the pits was measured with a depth micrometer. The micrometer was calibrated before and checked after use by the EPA contractor's instrumentation services group. While the specified micrometer has a resolution of 0.001-in., the accuracy is on the order of ±0.010-in. because of the pipe surface roughness, surface preparation, and other measurement variables. The depth was measured in a grid pattern throughout the anomalous region. A ½ × ½-in. grid was established using hardware cloth as seen in Figure 4-1. A bridging bar, shown in Figure 4-2 was used as a reference position to make measurements. The micrometer was zeroed on pipe without metal loss at the left of the anomalous region and the height at the right of the anomalous region was adjusted until pipe without metal loss measured zero. The recorded data shows these zero readings. The anomalous regions were photographed with a tape measure next to the region for scaling with zero length starting at the spigot end of the pipe. The micrometer had a digital output that would transfer the reading to a Microsoft Excel$^{TM}$ spreadsheet. The grids were numbered on the pipe to ensure that the grid location corresponded to the Excel$^{TM}$ cell numbers. The entire measurement system is shown in Figure 4-3. This automated process eliminated data recording errors and improved accuracy. One depth measurement was taken in each ½ x ½-in. square. A typical anomalous region had thousands of measurements and, even with automation, this process proved to be labor intensive. Hence, only the five largest anomalous regions on each pipe were evaluated. In the original QAPP plan, one out of five measurements was to be repeated. Because of the improved process, this was considered excessive and 1 or 2 repeat measurements per row were performed to ensure quality.

Figure 4-1. Hardware Cloth on Pipe Sample with Corrosion Used to Establish the ½-x½-in., Grid

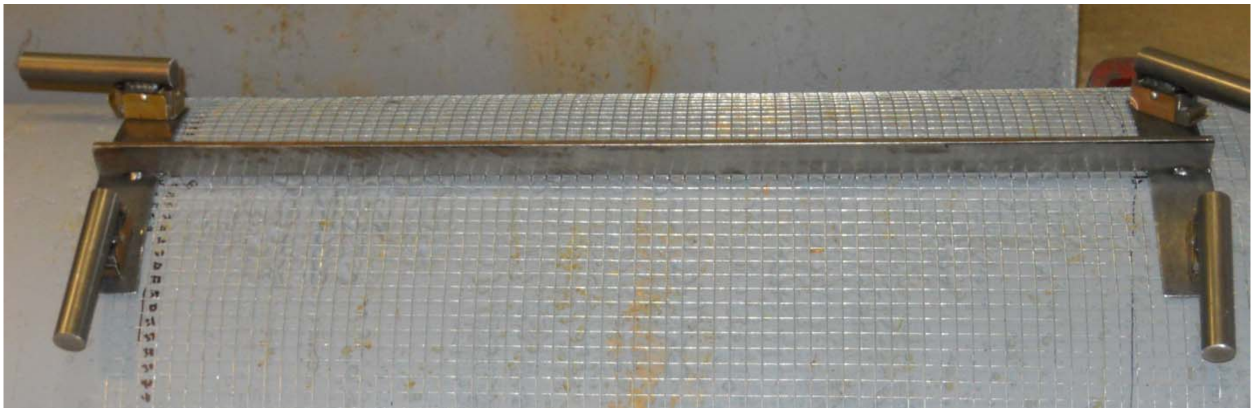

**Figure 4-2. Bridging Bar Used to Establish a Reference for Measurements**

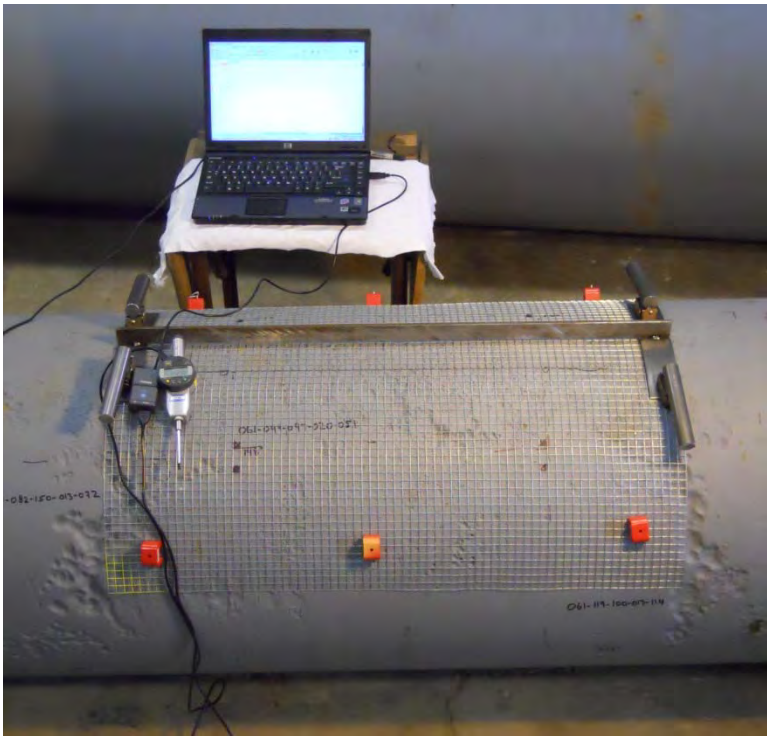

**Figure 4-3. Data Recording System for Making Depth Measurements**

A typical result of the metal loss evaluation is shown in Figures 4-4 and 4-5. Figure 4-4 shows the corrosion area on pipe 69 (at 95-in. from the spigot, 129-degrees from the top of the pipe, 27-in. in axial extent, and 109-degrees in circumferential extent). Figure 4-5 shows a color coded depth area contour map. Each color change corresponds to a change in depth of 0.05-in. While corrosion is present throughout the region, the deepest corrosion is more severe on the left side of the anomalous region shown. The deepest pit is between 0.35- and 0.40-in., or 50% of the pipe wall thickness.

**Figure 4-4. Corrosion Area on Pipe 69: 95-in. from the spigot, 129-degrees from the top of the pipe, 27-in. in axial extent and 109-degrees in circumferential extent**

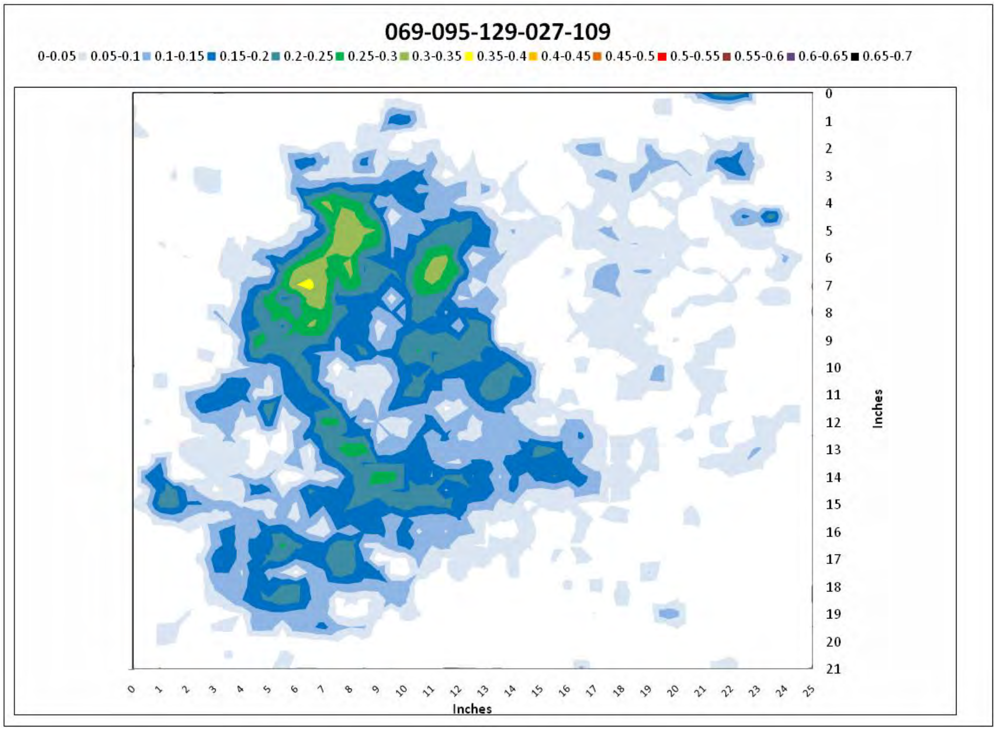

**Figure 4-5. Map of Corrosion Area on Pipe 69: 95-in. from the spigot, 129-degrees from the top of the pipe, 27-in. in axial extent and 109-degrees in circumferential extent**

**Automated Assessment of Wall Loss.** A laser based coordinate-measuring machine (CMM) was used for automated measurement of the four pipes selected for verification and judged to be in the worst condition. This method uses laser beams that are projected against the surface of the pipe. Many thousands of points are then taken and used to determine the size and position of corrosion by creating a three-dimensional (3D) image of the pipe. This point data is then transferred to computer-aided digital software to create a working 3D model of the pipe. The laser scanner is often used to facilitate the "reverse engineering" of complex components by taking an existing part, measuring it to determine its size, and creating engineering drawings from these measurements. The CMM technology used in this study was supplied by ApplusRTD. For this project, the equipment was supplied from its office in Houston, TX, which focuses on pipeline applications. Two operators provided a service on site at the EPA contractor's pipeline test facility.

For pipes, the cylindrical geometry is easily applied to assess corrosion, graphitization, and other anomalies. One limitation of the accuracy in the process is the quality of the original manufacturing process. Any natural deviation of the pipe from the assumed cylindrical geometry will produce a systematic metal loss or gain. While this limitation is not avoidable and systematic metal loss or gain cannot be separated from loss due to corrosion, the error is less than other methods that could be used to assess wall thickness over large areas. The method will only assess the external cast iron surface, not the liner.

Since the CMM technology is equally accurate for metal loss or gain, there is a simple method for verifying its accuracy. The accuracy of the CMM unit was checked with shim stock of known thicknesses affixed to the pipe surface in a region without anomalies. Shims of 10%, 25%, and 50% of wall thickness were attached to the pipe surface and assessed. The accuracy of the unit was within 0.040-in. , which is 5% of the 0.75-in. nominal wall thickness.

Grid size is a key variable. For example, with the resolution of 2.5-mm, about 100 data points will be taken for each square inch of pipe, or 1.2 million points for a 12-ft pipe segment. While this was the resolution that was initially planned, on site analysis indicated that a higher resolution was need to reconstruct the corrosion and pipe geometry. The number and complexity of anomalies with fine features dictated the need for a smaller resolution. A final resolution of 2-mm in the axial direction and 1-mm in the circumferential direction was used, which equates to about 322 data points for each square inch of pipe, or 3.8 million data points for a 12 ft pipe segment. The data was imported into a Microsoft Excel$^{TM}$ spreadsheet with about 2,000 rows and columns and a file size of over 60 megabytes. The scanning of each pipe required approximately one day.

Figure 4-6 shows the laser scanning of Pipe 63. The handheld CMM unit is in the upper left hand corner. The white dots, referred to as targets, are applied to areas of the pipe without metal loss. The coordinates of these points enables the establishment of a reference cylinder for estimating corrosion depth. A typical result is seen via laser scan in Figure 4-7 and via normal photography in Figure 4-8.

The CMM laser and manual methods were compared for a region of Pipe 63. The depths of 20 pits are shown in Table 4-10, and the differences between the two measurements are calculated. The depths varied about 7% depending on the clock position. Note that the clock position reported by the methods had about a 9 degree (i.e., 2.5%) variation.

As discussed previously, 12 pipes were sandblasted to expose the corrosion areas. While the corrosion extent was measured for all 12 pipes, four pipes were CMM laser mapped and eight pipes were assessed using the manual methods. Selection was based on visual assessment of the extent of the corrosion in the pipe segment and vendor recommendations. Pipes 56, 63, and 64 had extensive corrosion and were assessed with the CMM laser. Also assessed by laser were pipe segments 145/146 from Pit F, which were still together at the bell and spigot joint, and were extensively assessed by AESL ECAT and RSG HSK.

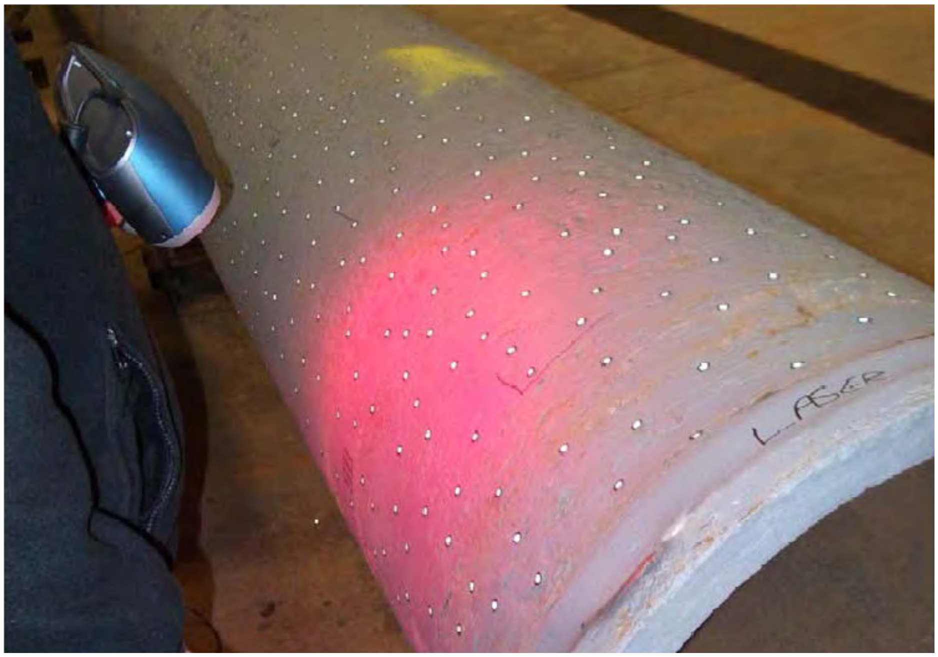

Figure 4-6. CMM Laser Scanning of Pipe 63

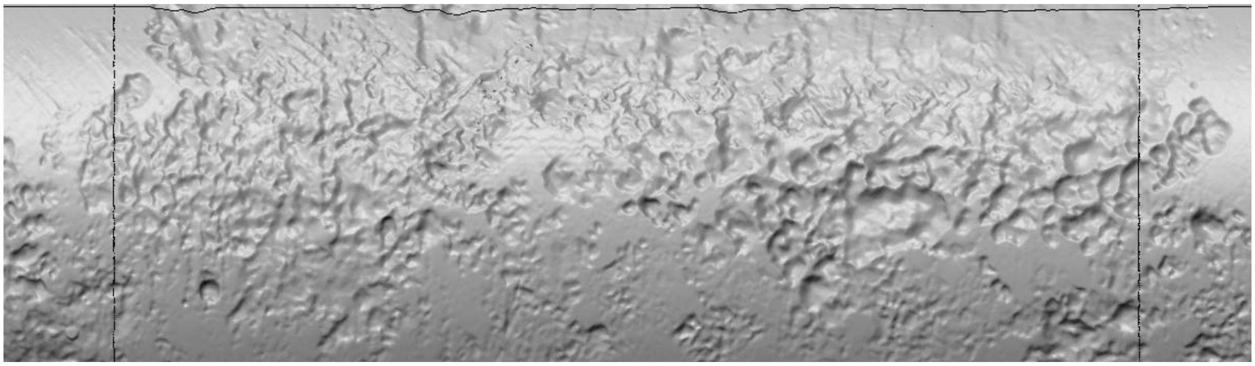

Figure 4-7. CMM Laser Scan Image of Pipe 63

Figure 4-8. Photograph of Pipe 63

Table 4-10. Depth of 20 Pits Measured on Pipe 63 by Laser and Manual Methods

| **Dist From Bell (in.)** | | **Clock (Degrees)** | | **Maximum Depths in Defect Area (in.)** | | **Delta** | **% Loss** | | **Delta** |
|---|---|---|---|---|---|---|---|---|---|
| **Laser** | **Manual** | **Laser** | **Manual** | **Laser** | **Manual** | | **Laser** | **Manual** | |
| 40.5 | 40.0 | 126 | 115 | 0.282 | 0.225 | 0.057 | 36% | 29% | 7% |
| 43.5 | 43 | 124 | 115 | 0.308 | 0.264 | 0.044 | 39% | 34% | 6% |
| 42.5 | 42 | 129 | 120 | 0.289 | 0.236 | 0.053 | 37% | 30% | 7% |
| 44 | 43.5 | 133 | 124 | 0.332 | 0.289 | 0.043 | 42% | 37% | 6% |
| 45 | 44.5 | 156 | 146 | 0.299 | 0.248 | 0.051 | 38% | 32% | 7% |
| 42.5 | 42 | 160 | 151 | 0.273 | 0.222 | 0.051 | 35% | 28% | 6% |
| 40.5 | 40.0 | 164 | 153 | 0.334 | 0.282 | 0.051 | 42% | 36% | 7% |
| 37.0 | 36.0 | 162 | 151 | 0.333 | 0.294 | 0.039 | 42% | 37% | 5% |
| 42.5 | 42.0 | 171 | 160 | 0.267 | 0.217 | 0.050 | 34% | 28% | 6% |
| 38.5 | 38.0 | 171 | 160 | 0.400 | 0.352 | 0.048 | 51% | 45% | 6% |
| 38.0 | 37.5 | 178 | 168 | 0.309 | 0.284 | 0.025 | 39% | 36% | 3% |
| 45.0 | 44.0 | 202 | 193 | 0.244 | 0.287 | -0.043 | 31% | 37% | -5% |
| 42.0 | 41.5 | 204 | 193 | 0.214 | 0.284 | -0.070 | 27% | 36% | -9% |
| 41.5 | 41.5 | 198 | 186 | 0.230 | 0.214 | 0.016 | 29% | 27% | 2% |
| 38.5 | 38.0 | 202 | 191 | 0.227 | 0.264 | -0.037 | 29% | 34% | -5% |
| 46.5 | 46.0 | 209 | 199 | 0.264 | 0.265 | -0.001 | 34% | 34% | 0% |
| 44.0 | 43.5 | 213 | 204 | 0.206 | 0.257 | -0.051 | 26% | 33% | -7% |
| 46.0 | 45.5 | 218 | 208 | 0.178 | 0.227 | -0.049 | 23% | 29% | -6% |
| 45.0 | 44.5 | 218 | 208 | 0.237 | 0.288 | -0.051 | 30% | 37% | -6% |
| 41.0 | 40.5 | 218 | 208 | 0.181 | 0.225 | -0.044 | 23% | 29% | -6% |

## 4.6 Summary of the Extent of Corrosion on Pipes Selected for Post-Demonstration Verification

The extent of metal loss for each pipe sample is summarized in Table 4-11. Four criteria were used to rate the 12 pipe samples:

- Total volume loss
- Number of deep pits greater than 50% depth
- Maximum pit depth
- Largest corrosion patch assessment.

While none of the pipe appeared to have significant degradations, the pipes were assigned a relative severity based on these four criteria with class 1 being the most severe and class 4 being the least severe. For the most severe, Pipe 49 was chosen because of the large number of deep pits and pipes 63 and 64 were chosen for the large volume loss and some deep pits. For relative class 2, pipes 32, 61 and 69 were chosen for the moderate volume loss and some deep pits. Pipes 30, 98 and 137 had minimal volume loss and few if any deep pits and were assigned a relative rating of 4. The rest were a relative rating of 3.

## Table 4-11. Summary of Metal Loss for Each Destructively Assessed Pipe Sample

| Pipe # | Method | Volume Loss | | Deep Pits | | Max. Pit Depth | | Largest Patch | | Visual Assessment | Relative |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Percent | Relative | >50% | Relative | Max. Pit Depth | Rating | Length (in.) | Ave Depth | | |
| 30 | Manual | 0.2% | Minimal | 1 | Very few | 68% | Deep | 5 | 26% | Generally light corrosion with one deep pit | 4 |
| 32 | Manual | 0.7% | Small | 2 | Very few | 56% | Moderate | 22.5 | 35% | A long corrosion area with a moderately deep pit in the center. Generally light corrosion elsewhere. | 2 |
| 49 | Manual | 1.0% | Small | 13 | Most | 85% | Deep | 25.2 | 48% | A ~2 ft long corrosion area with many deep pits, one close to being through wall. Generally moderate corrosion elsewhere | 1 |
| 56 | Laser | 2.1% | Largest | 0 | Very few | 39% | Not deep | 60 | 22% | Large area of corrosion, however none of the corrosion areas were very deep | 3 |
| 61 | Manual | 1.4% | Medium | 6 | Some | 63% | Moderate | 26.5 | 28% | A few deep areas of corrosion. Significant amount of pipe with full wall thickness. | 2 |
| 63 | Laser | 2.6% | Largest | 6 | Some | 51% | Moderate | 40 | 32% | Large areas of corrosion with moderate depth. Some pipe with full wall thickness. | 1 |
| 64 | Laser | 2.1% | Largest | 5 | Some | 72% | Deep | 60 | 29% | Areas of corrosion with moderate depth and a few deep pits. Significant amount of pipe with full wall thickness. | 1 |
| 69 | Manual | 1.6% | Medium | 4 | Some | 75% | Deep | 14.5 | 33% | Moderate and a few deep corrosion pits, mostly in clusters. | 2 |
| 98 | Manual | 0.9% | Small | 1 | Very few | 63% | Moderate | 9.5 | 30% | Moderate corrosion pits, often in clusters. | 3 |
| 137 | Manual | 1.1% | Small | 0 | Very few | 46% | Moderate | 20 | 22% | Generally light corrosion. Clusters of shallow corrosion pits and large areas of pipe with full wall thickness. | 4 |
| 145/ 146 | Laser | 0.8% | Small | 2 | Very few | 55% | Moderate | 28.4 | 24% | Areas of shallow corrosion and areas of pipe with full wall thickness. Neither was a full length of pipe. | 3 |
| 166 | Manual | 0.3% | Minimal | 0 | Very few | 37% | Not deep | 20 | 15% | Light corrosion and areas of pipe with full wall thickness. | 4 |

# 5.0: RESULTS AND DISCUSSION

Each vendor was able to deploy their technology through mobilizing crews on site, setting up the equipment, operating the technology, collecting data, and providing the requested inspection reports. Detailed results for all of the pipe wall thickness assessment technologies are discussed in this section.

The individual inspection reports provided by each vendor are included in Appendix B (Sahara® Video, Sahara®WTT, and PipeDiver®), Appendix C (SmartBall™ PWA), Appendix D (ThicknessFinder), Appendix E (See Snake®), Appendix F (ECAT), and Appendix G (HSK and CAP).

Because this demonstration was a snapshot in time, new developments may have taken place since completion of the demonstration. Therefore, the findings in this report may not be wholly representative of the current operational capabilities of the demonstrated technologies. For this reason, the vendors were asked to provide formal comments on the acoustic pipe wall thickness assessment report to highlight advancements since completion of the demonstration and/or clarification on what was reported. These comment letters are contained in Appendix H. For current status of these technologies, see vendor websites, which are listed in the Executive Summary and Section 2 (Summary and Conclusions) to this report.

## 5.1 Acoustic Pipe Wall Thickness Assessment

The Sahara® WTT, SmartBall™ PWA, and ThicknessFinder acoustic pipe wall thickness assessment technologies were demonstrated on a 76-year-old, 2,057-ft-long portion of a cement-lined, 24-in. diameter cast iron water main in Louisville, KY. While each technology used some form of acoustic device, the implementations were quite different:

- Sahara® WTT uses a hydrophone sensor at the end of a cable tether. The hydrophone was inserted and pulled through the pipeline using the water flow. The sound energy used for the acoustic velocity measurement was generated by contacting the pipe at selected locations.
- The SmartBall™ PWA sensor and data-recording device were placed within a foam ball. The sensor and ball were inserted in the pipeline and propelled by the water through the pipeline to a downstream extraction point where a net inserted into the pipe caught and removed the unit. The sound energy was generated by a speaker in contact with the water placed at the ends and the middle of the test pipe.
- ThicknessFinder used pairs of accelerometers mounted on the outside of the pipe at discrete locations to measure sound velocity in the pipe to determine average pipe wall thickness. The sound was generated by an orifice.

### 5.1.1 Sahara® WTT.

The results of the wall thickness assessment are presented as an average wall thickness loss ratio (in 15% increments) over a 33 ft interval. EPA's contractor performed a detailed assessment of seven exhumed, 12-ft pipe segments that fell within the 33-ft spans of pipe where average wall thickness loss was determined by Sahara®WTT. The two sets of results are compared.

**Summary of Results.** Sahara® WTT assessment was performed in conjunction with their leak detection assessment. Analysis of the Sahara® WTT results uncovered specific intervals of the pipeline with higher wall thickness loss than other pipeline intervals. Details of the wall thickness loss are presented in Table 5-1 and specify the pipeline interval (~33 ft) and average wall thickness loss over that interval.

## Table 5-1. Sahara® Wall Thickness Results

| Distance from Start (ft) | Average Wall Thickness Loss Ratio (%)[19] | Distance from Start (ft) | Average Wall Thickness Loss Ratio (%) |
|---|---|---|---|
| 0-17 | Results not available | 590-623 | Nominal |
| 17-33 | < 15% | 623-656 | < 15% |
| 33-66 | Nominal | 656-689 | Nominal |
| 66-98 | < 15% | 689-722 | 15-30% |
| 98-131 | Nominal | 722-754 | 15-30% |
| 131-164 | Nominal | 754-787 | Nominal |
| 164-197 | Nominal | 787-1640 | Results not available |
| 197-230 | 15-30% | 1640-1673 | Nominal |
| 230-295 | Results not available | 1673-1706 | Nominal |
| 295-328 | > 30% | 1706-1738 | < 15% |
| 328-361 | > 30% | 1738-1771 | < 15% |
| 361-394 | > 30% | 1771-1804 | < 15% |
| 394-426 | Nominal | 1804-1837 | < 15% |
| 426-459 | < 15% | 1837-1870 | Nominal |
| 459-492 | 15-30% | 1870-1902 | Nominal |
| 492-525 | < 15% | 1902-1935 | 15-30% |
| 525-558 | < 15% | 1935-2057 | Results not available |
| 558-590 | < 15% | - | - |
| 590-623 | Nominal | - | - |

The vendor defined nominal loss of pipe wall thickness as less than 2%. Three pipe sections ([295 to 328 ft], [328 to 361 ft], and [361 to 394 ft]), showed the highest wall thickness loss (i.e., >30%). Five sections showed 15% to 30% of wall thickness loss. Eleven pipe sections showed <15% of wall thickness loss. The remaining sections showed nominal wall loss. However, a wall thickness ratio could not be calculated for several pipe sections comprising about 1040 ft of the 2057 ft test pipe, (i.e., [230 to 295 ft], [787 to 1,640 ft], and [1,935 to 2,057 ft]), due to reasons such as the close proximity of the internal and external sensors, presence of large air pockets, or noise from the pipeline discharge, which masked acoustic activity after 1,935 ft.

**Comparison to Assessed Pipe Samples.** Sahara® WTT provided average wall loss results for 32 intervals that were typically 33-ft in length. For seven of these 33-ft intervals, each one had a 12-ft length of pipe characterized in detail by EPA’s contractor. The data from the 33-ft interval and the corresponding 12-ft pipe length were compared to determine whether they appeared to be in rough agreement. The results are given in Table 5-2. The data from the seven pipe lengths were compiled in several ways to facilitate several types of comparisons: (1) volume loss, (2) number of pits deeper than 50% wall thickness, (3) maximum pit depth, and (4) largest patch (i.e., a combination of depth and length). A summary visual assessment and the numerical results of the 4-level, relative condition ranking are also included in Table 5-2. For the seven pipe sections that included a length of pipe that was exhumed and characterized by EPA’s contractor, Sahara® WTT predicted two pipe sections with average wall loss >30%, three pipe sections with average wall loss between 15%-30%, and two pipe sections <15% wall loss. However, the exhumed pipes that were fully assessed within those sections had limited variation with an average wall loss of no more than 2.6 % .. Therefore, predicted values for five of the seven 33-ft pipe sections reported by Sahara® WTT did not correlate with condition of the included, exhumed pipe. Furthermore, the average wall loss measurements did not correlate with the number of deep pits, the maximum pit depth, the severity of the largest patch, the visual assessment, or the 4-level relative ranking system.

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[19] Pipeline intervals with an average wall thickness loss of less than 2% are listed as nominal. The average wall thickness loss ratio is in relation to the nominal mean value.

**Table 5-2. Results for Sahara® WTT and Seven Included, Destructively Assessed Pipes**

| Pipe # | Method | Wall Thickness Loss Ratio | Volume Loss | | Deep Pits >50% | Rating | Max. Pit Depth | Rating | Largest Patch | | Visual Assessment | Relative |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Percent | Relative | | | | | Length (in.) | Depth | | |
| 30 | Manual | >30% | 0.2% | Minimal | 1 | Very few | 68% | Deep | 5 | 26% | Generally light corrosion with one deep pit. | 4 |
| 32 | Manual | >30% | 0.7% | Small | 2 | Very few | 56% | Moderate | 22.5 | 35% | A long corrosion area with a moderately deep corrosion pit in the center. Generally light corrosion elsewhere. | 2 |
| 49 | Manual | <15% | 1.0% | Small | 13 | Most | 85% | Deep | 25.2 | 48% | A 2 ft long corrosion area with many deep pits, one near through wall. Generally moderate corrosion elsewhere | 1 |
| 56 | Laser | <15% | 2.1% | Largest | 0 | None | 39% | Not deep | 60 | 22% | Large area of corrosion, however none very deep. | 3 |
| 61 | Manual | 15-30% | 1.4% | Medium | 6 | Some | 63% | Moderate | 26.5 | 28% | A few deep areas of corrosion. Significant amount of pipe with full wall thickness. | 2 |
| 63 | Laser | 15-30% | 2.6% | Largest | 6 | Some | 51% | Moderate | 40 | 32% | Large areas of corrosion with moderate depth. Some pipe with full wall thickness. | 1 |
| 64 | Laser | 15-30% | 2.1% | Largest | 5 | Some | 72% | Deep | 60 | 29% | Areas of corrosion with moderate depth and a few deep corrosion pits. Significant amount of pipe with full wall thickness. | 1 |

**Discussion.** Sahara® WTT provided results that indicated that a wide range of conditions were present in the pipe. However, the pipe was found to have minimal wall loss degradation based upon the post-demonstration confirmation study. It is possible the vendor conservatively estimated average wall thickness by assigning the largest velocity changes to a significant loss. The results of the post-confirmation study suggest that additional vendor experience with excavation information is needed to improve calibration of the tool and reduce the amount of over calls. Also, since the test pipe appeared to have minimal overall wall loss (e.g., $\leq$ 2.6 % wall loss in the 12 exhumed sections), the capability of this and other wall thickness screening technologies to successfully identify severely corroded pipe could not be assessed, so that remains a topic for future evaluation.

By utilizing the tethered Sahara® system and being able to stop the hydrophone at precise locations, the Sahara® WTT technique allows more flexible distance and selectable intervals for calculating average wall thickness loss; finer intervals (better resolution) can be selected at the cost of longer inspection times. Knowledge of average wall thickness in a pipe section does not identify specific defects, but it could be used for focusing subsequent, more detailed and expensive structural inspections on the most problematic areas.

### 5.1.2 SmartBall™ Pipe Wall Assessment.

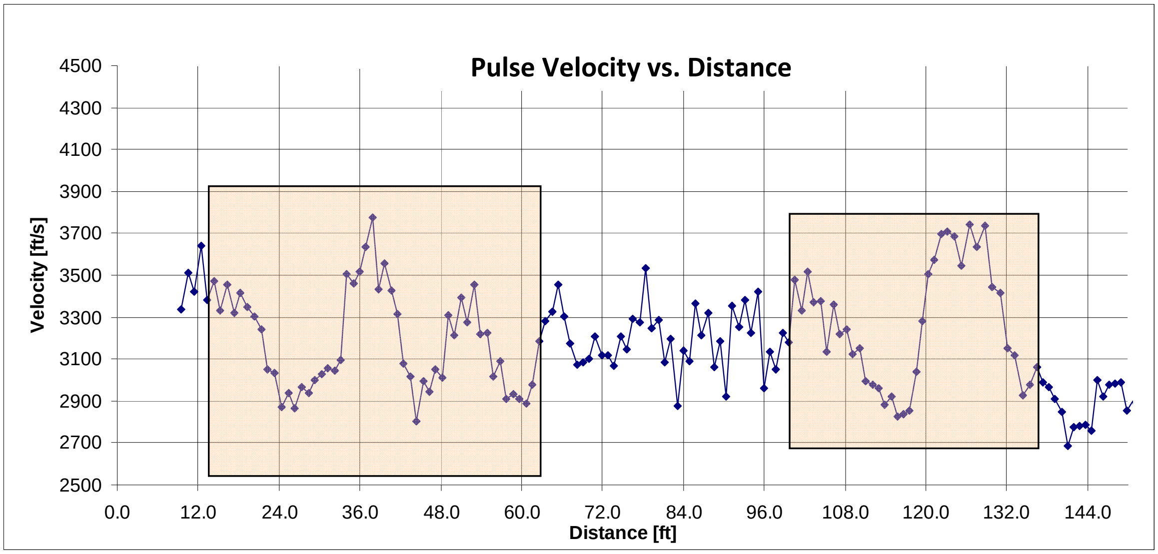
SmartBall™ PWA reported the wall thickness assessment results as general intervals of interest with reduced wall stiffness for the first 1,050 ft of the test pipe. It had difficulties assessing the second half of the test pipe potentially due to SmartBall™ PWA being unable to detect the signal from the third pulser, which was nearest the large amount of noise produced by discharge of water from the test pipe. The signals from the first and second pulsers were detectable and those results are summarized below.

EPA’s contractor performed a detailed assessment of 12 pipe segments to compare the metal loss data from the pipes selected for verification with the area of suspected wall loss reported by SmartBall™ PWA. The same four point rating system was used to describe the metal loss defect’s impact on the pipeline condition. Similarly, because SmartBall™ PWA presented results over intervals longer than one pipe segment the results could not be completely verified due to the limited number of exhumed pipe segments.

**Summary of Results.** Upon retrieval of the tool, the acoustic, time, and position data recorded by the SmartBall™ PWA were analyzed and cross-referenced with the acoustic, time, and position data from the fixed SBRs and the pulsers to determine the acoustic velocity for consecutive, short intervals of the pipe during the inspection.

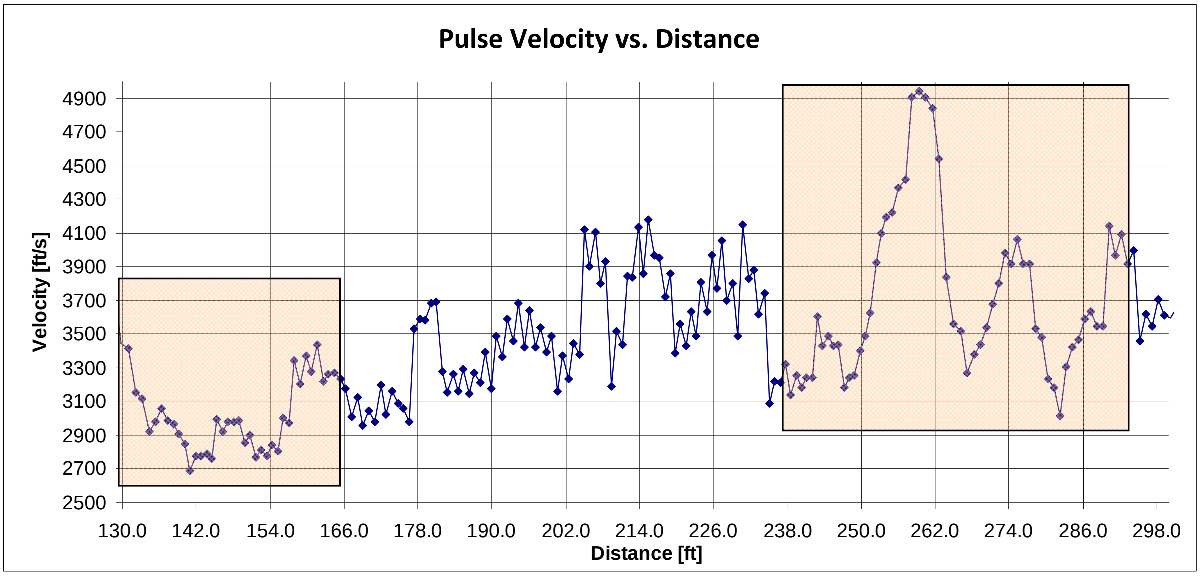
The graphs in Figure 5-1 through Figure 5-7 show the condition of the pipe as detected by the SmartBall™ PWA with respect to its distance along the pipeline. Since the pipe wall thickness is directly proportional to the velocity of the signal as it propagates through a water filled pipe, these graphs indicate that there is some evidence of pipe wall stiffness changes within the highlighted areas. However, although the data suggests that several interesting variations exist in the pulse velocity at different points along the pipeline, it was unclear whether the data revealed actual changes in the hoop stiffness of the pipe wall, or if the data had been affected by the presence or condition of the mortar lining or other pipe stiffness enhancements (such as previous repairs on the pipe). This is a common issue for acoustic-based technologies.

Table 5-3 provides a summary of the locations with evidence of pipe wall weakness up to the second pulser location. In addition, the SmartBall™ PWA was able, in some portions of the pipeline, to detect features such as valves and joints based on increased acoustic velocity. For example, the acoustic profile showed increased acoustic velocities at, or in the vicinity of, the 12-ft intervals of the joints (see Figure 5-8) and at a drain valve approximately 260 ft from the insertion location (see Figure 5-9). The spatial resolution of the tool factored in the flow velocity and was at least one data point every two ft along the line. This technique is not designed to detect individual pits, but may reveal areas where clusters of pitting or thinning produce weakening over several feet along the pipe.



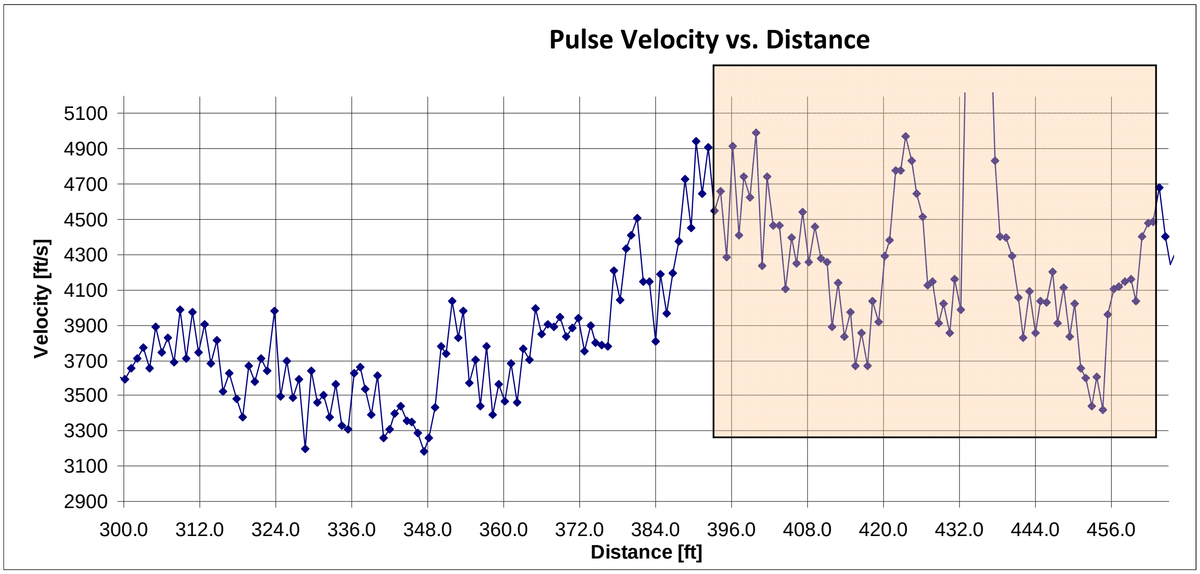
(Courtesy of Pure)

Figure 5-1. Acoustic Profiles from 0 ft to 150 ft



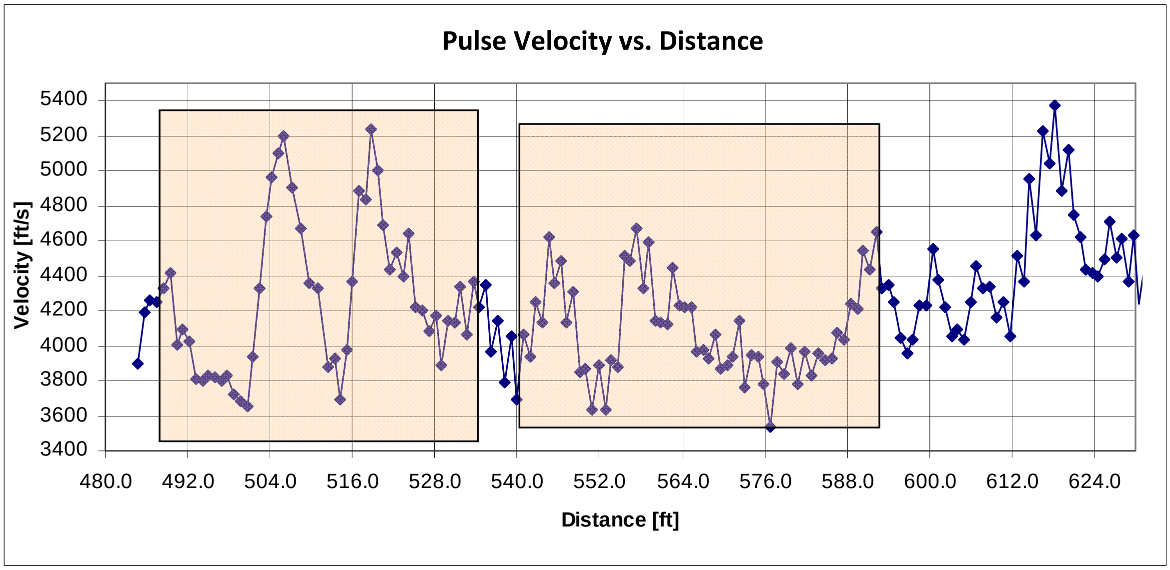
(Courtesy of Pure)

Figure 5-2. Acoustic Profiles from 130 ft to 300 ft



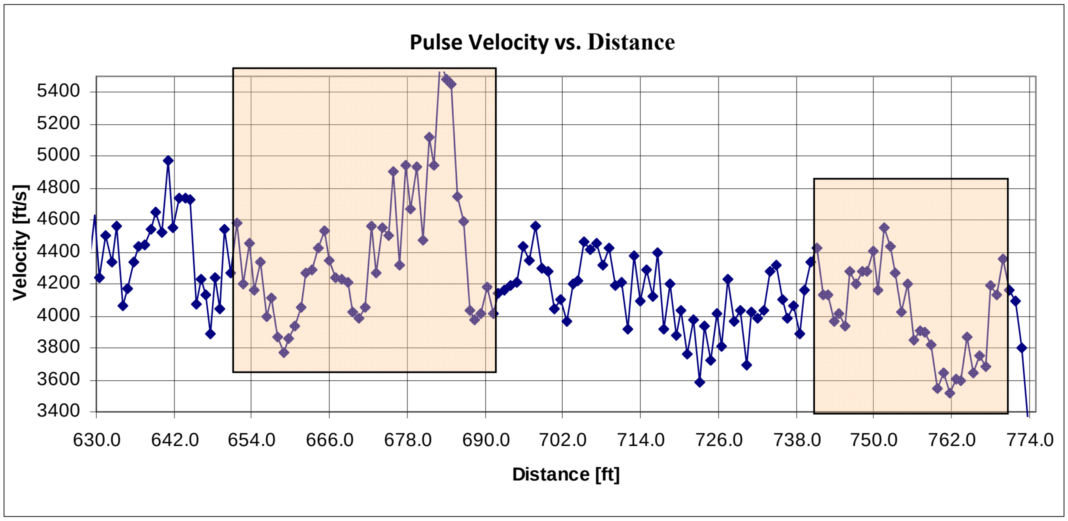
(Courtesy of Pure)

**Figure 5-3. Acoustic Profiles from 300 ft to 465 ft**



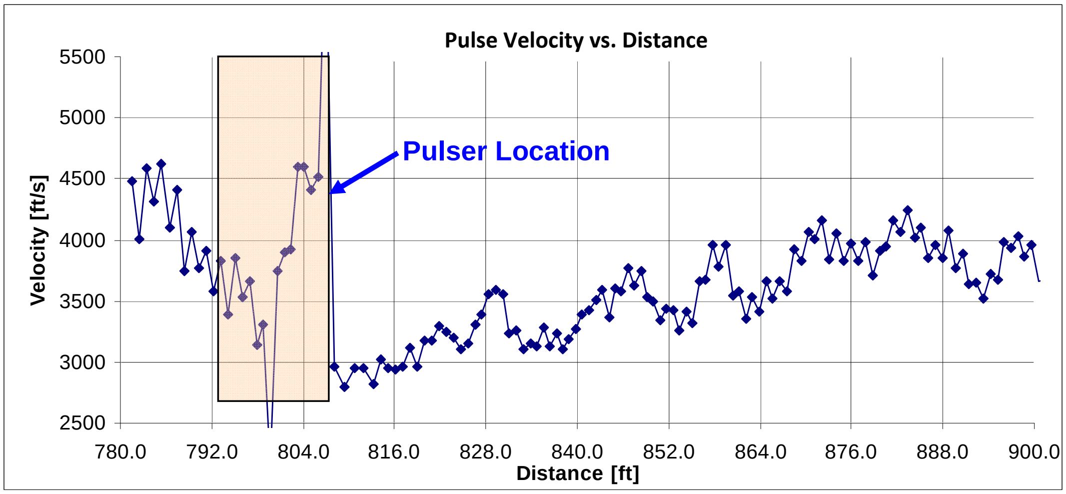
(Courtesy of Pure)

**Figure 5-4. Acoustic Profiles from 480 ft to 630 ft**



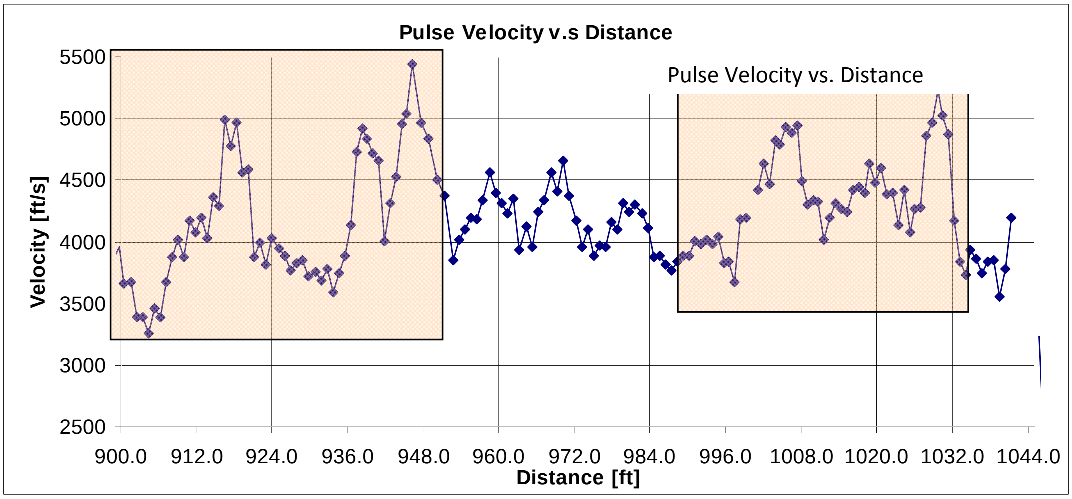
(Courtesy of Pure)

Figure 5-5.  Acoustic Profiles from 630 ft to 775 ft



(Courtesy of Pure)

Figure 5-6.  Acoustic Profiles from 780 ft to 900 ft

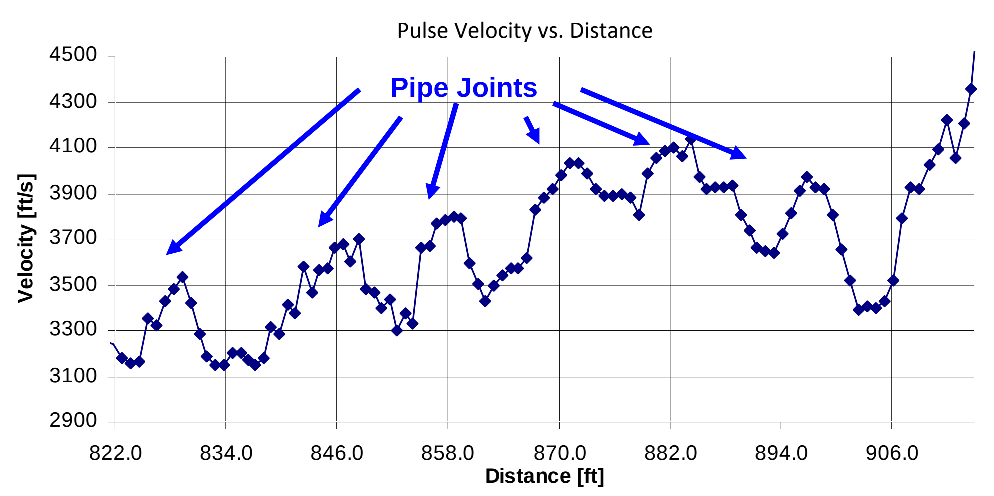


(Courtesy of Pure)

**Figure 5-7.  Acoustic Profiles from 900 ft to 1,050 ft**

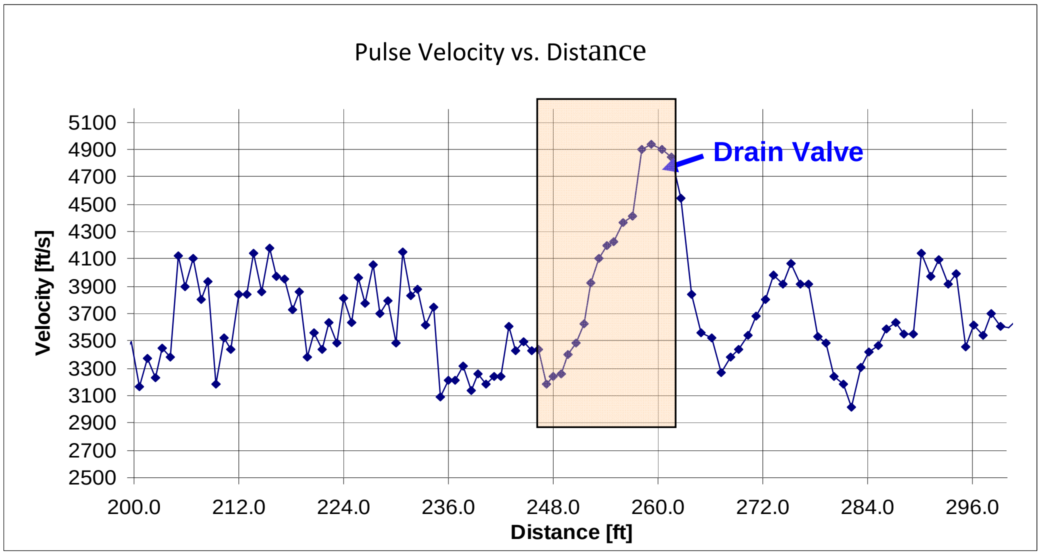
**Table 5-3.  PWA Wall Thickness Results – Summary of Acoustic Anomalies**

| Location of Interest | Sections of Interest Downstream from Launch Point |
|---|---|
| 1 | 14 ft to 63 ft |
| 2 | 100 ft to 138 ft |
| 3 | 130 ft to 165 ft |
| 4 | 237 ft to 292ft |
| 5 | 393 ft to 465 ft |
| 6 | 488 ft to 535 ft |
| 7 | 540 ft to 592 ft |
| 8 | 650 ft to 692 ft |
| 9 | 742 ft to 770 ft |
| 10 | 794 ft to 808 ft |
| 11 | 900 ft to 950 ft |
| 12 | 990 ft to 1,034 ft |



(Courtesy of Pure)

**Figure 5-8. Joint Locations**



(Courtesy of Pure)

**Figure 5-9. Drain Valve Location as Seen by Acoustic Pulses**

**Comparison to Assessed Pipe Samples.** SmartBall PWA provided results for approximately the first half of the test section, which corresponds to 7 of the 12 pipes that were fully assessed by EPA's contractor. The results are given in Table 5-4. For the other 5 pipes, pipeline and inspection variables adversely affected data collection and therefore SmartBall$^{TM}$ PWA was unable to provide results. Pure identified four areas of reduced stiffness and three areas where the pipe was normal. The three relatively worse pipes were identified as having reduced wall thickness. These pipes had either a larger volume of metal loss or a larger area of corrosion with deep pits. One of the pipes identified as being potentially damaged had a low volume loss and relatively moderate pitting. Two of the pipes identified as normal had minimal volume loss and only a few deep pits. One of the pipes identified as normal had metal loss pitting over a large area, but none of the pit depths exceeded 40%.

Table 5-4. Results for Pure SmartBall™ Pipe Wall Assessment (PWA) and Seven Included, Destructively Assessed Pipes

| **Pipe #** | **Method** | **SmartBall™ Condition Rating for Span with included Pipe** | **Volume Loss** | | **Deep Pits >50%** | **Rating** | **Max Pit Depth** | **Rating** | **Largest Patch** | | **Visual Assessment** | **Relative** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Percent** | **Relative** | | | | | **Length (in.)** | **Depth** | | |
| 30 | Manual | Normal | 0.2% | Minimal | 1 | Very few | 68% | Deep | 5 | 26% | Generally light corrosion with one deep pit | 4 |
| 32 | Manual | Normal | 0.7% | Small | 2 | Very few | 56% | Moderate | 22.5 | 35% | A long corrosion area with a moderately deep corrosion pit in the center. Generally light corrosion elsewhere. | 2 |
| 49 | Manual | Reduced stiffness | 1.0% | Small | 13 | Most | 85% | Deep | 25.2 | 48% | A 2 ft long corrosion area with many deep corrosion pits, one near through wall. Generally moderate corrosion elsewhere | 1 |
| 56 | Laser | Normal | 2.1% | Largest | 0 | None | 39% | Not deep | 60 | 22% | Large area of corrosion, however none very deep | 3 |
| 61 | Manual | Reduced stiffness | 1.4% | Medium | 6 | Some | 63% | Moderate | 26.5 | 28% | A few deep areas of corrosion. Significant amount of pipe with full wall thickness | 2 |
| 63 | Laser | Reduced stiffness | 2.6% | Largest | 6 | Some | 51% | Moderate | 40 | 32% | Large areas of corrosion with moderate depth. Some pipe with full wall thickness | 1 |
| 64 | Laser | Reduced stiffness | 2.1% | Largest | 5 | Some | 72% | Deep | 60 | 29% | Areas of corrosion with moderate depth and a few deep corrosion pits. Significant pipe with full wall thickness | 1 |

**Discussion.** Pipes with significant degradation, though desired for this demonstration, were not part of this water main. Nonetheless, within the level of degradation that was available, SmartBall$^{TM}$ PWA provided wall thickness estimates for spans of pipe that were usually consistent with the relative condition, as determined by EPA's contractor, of the exhumed 12-ft pipe contained in the span. From the results of the post-confirmation study, it may also be inferred that some segments of the pipe were improperly assessed and that additional vendor experience with excavated, characterized pipe information is needed, especially to better calibrate results for pipes with minimal wall thickness loss. Given the overall good condition of the pipe in this demonstration, there is also a need for further evaluation for pipes with severe wall loss due to corrosion or other causes. Some capability to detect the extra wall thickness at bell and spigot joints and a drain valve was demonstrated.

The high density of the measurements provided by SmartBall$^{TM}$ PWA could prove useful for average wall thickness measurements on a segment by segment basis. Analysis methods continue to be improved for this emerging inspection methodology.

### 5.1.3 ThicknessFinder.

ThicknessFinder reported the condition assessment results as the remaining equivalent thickness of the pipe. The equivalent thickness of a cement-lined metallic pipe is the thickness of an un-lined metallic pipe that would be required to match the structural stiffness of the cement-lined pipe. Since the cement lining enhances the structural stiffness of the pipe, the equivalent thickness of a cement-lined metallic pipe is generally thicker than the actual metal pipe. The 2,057-ft long test pipe was divided into seven sections. Each section was bracketed by access pits where acoustic sensors were attached; the sections ranged in length from approximately 250 to 360 ft (averaging 293 ft).

**Summary of Results.** Based on current and previous analyses using ThicknessFinder, Echologics recommended the guidelines presented in Table 5-5 for interpreting their wall thickness data.

**Table 5-5. Guidelines for Interpreting ThicknessFinder Wall Thickness Data**

| Wall Loss (%) | Description of Pipe Condition |
|---|---|
| 0-10 | The pipe is in very good condition, but may still have minor levels of uniform corrosion. Some localized areas of pitting corrosion may exist but it is expected that the areas are isolated. |
| 10-20 | Pipe is in good condition, there may be some moderate uniform surface or internal corrosion, or more localized areas of pitting corrosion. |
| 20-35 | Pipe may have significant localized areas of pitting corrosion, or moderate uniform corrosion throughout. |
| >35 | Pipe is in poor condition and may have numerous areas of pitting corrosion, including significant uniform thinning of the pipe. |

The results of the condition assessment measurements are presented in Table 5-6. Six sections in a row presented remaining equivalent thickness greater than 0.70-in. with the seventh section .01-in. below, at 0.69-in. Echologics concluded that there may be some deterioration in these sections and that the pipe is in good structural condition, which they define in Table 5-5 as having wall loss in the 10%-20% range. They more specifically estimated the effective wall thickness loss to be approximately 14%-20%.

Table 5-6. Echologics ThicknessFinder Condition Assessment Results

| File # | Location | Sensor-to-Sensor Spacing (ft) | Measured Average Thickness (in.) | Condition |
|---|---|---|---|---|
| 1a | Pit 1 to Pit A | 250.7 | 0.73 | Good |
| 2c | Pit A to Pit B | 260.5 | 0.74 | Good |
| 3c | Pit B to Pit C | 298.6 | 0.75 | Good |
| 4b | Pit C to Pit 2 | 271 | 0.71 | Good |
| 5d | Pit 2 to Pit E | 360.9 | 0.71 | Good |
| 6c | Pit E to Pit F | 294.6 | 0.72 | Good |
| 7b | Pit F to Pit 3 | 312.7 | 0.69 | Good |

**Comparison to Assessed Pipe Samples.** Echologics provided results for the entire pipe length used in the demonstration. ThicknessFinder was operated with the pipe full, but not flowing, and in this operating mode there is no need for a noisy discharge to the sewer, as was required for transporting Sahara® WTT and SmartBall™ PWA through the pipe. The results are given in Table 5-7.

**Discussion.** ThicknessFinder provided average wall thickness values over 250 ft to 360 ft intervals. The reported results showed that all pipes were in "good" condition per Echologics' definition of the term, and loss from the effective wall thickness was in the 14%-20% range. Thus ThicknessFinder reported wall loss that was about 11% to 17% more severe than the maximum average wall loss (i.e., 2.6 %) determined by the destructive assessment results and other findings that indicated that pipes with significant degradation were not part of this water main. The reported inspection results contained a slight variation (~7%) from Pit F to Pit 3, which may have indicated an area with slightly more metal loss. Because of the large inspection interval and the small number of pipes that were exhumed and characterized in detail, this reported variation could not be confirmed ThicknessFinder was not designed to, nor did it appear to be able to, discriminate between slight variations in the condition of locally degraded pipe.

## 5.2 Internal Inspection

The Sahara Video®, PipeDiver® RFEC, and See Snake® RFT internal inspection technologies were demonstrated on the same cast iron water main in Louisville, KY as described above. Sahara Video® used CCTV to conduct an internal inspection of the pipeline, while PipeDiver® and See Snake® used a form of RFEC technology. The inspections were conducted as follows:

- Sahara Video® uses a video camera at the end of a cable tether. The camera, which was inserted and pulled through the pipeline using the water flow, provided real-time, in-service CCTV inspection of the test pipe. The camera was also tracked by an operator from ground level to mark items of interest on the pavement.
- PipeDiver® RFEC is a non-tethered, free swimming platform for inspection of in-service water mains and includes an electronics module, battery module, and transmitter module for above ground tracking. PipeDiver® is inserted and extracted from the water pipe via large, vertical tubes designed to launch or receive the tool at pipeline pressures.
- See Snake® RFT was pulled though the main, which was emptied and swabbed. The hard diameter of the tool is smaller than the ID of the pipe to allow for passage around protrusions, lining, and scale within the pipe. Centralizers maintain a uniform annulus between the tool and the pipe. The vendor indicates that future versions can be made for in-service mains.

**Table 5-7. Echologics ThicknessFinder Condition Assessment Results for Eleven Destructively Assessed Pipes**[20]

| Pipe # | Method | ThicknessFinder Equivalent Thickness (Includes Coating) | Volume Loss | | Deep Pits >50% | Rating | Max. Pit Depth | Rating | Largest Patch | | Visual Assessment | Relat ive |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Percent | Relative | | | | | Length (in.) | Depth | | |
| 30 | Manual | 0.74-in. | 0.2% | Minimal | 1 | Very few | 68% | Deep | 5 | 26% | Generally light corrosion with one deep corrosion pit | 4 |
| 32 | Manual | 0.74-in. | 0.7% | Small | 2 | Very few | 56% | Moderate | 22.5 | 35% | A long corrosion area with a moderately deep corrosion pit in the center. Generally light corrosion elsewhere. | 2 |
| 49 | Manual | 0.75-in. | 1.0% | Small | 13 | Most | 85% | Deep | 25.2 | 48% | A 2 ft long corrosion area with many deep corrosion pits, one near through wall. Generally moderate corrosion elsewhere | 1 |
| 56 | Laser | 0.75-in. | 2.1% | Largest | 0 | Very few | 39% | Not deep | 60 | 22% | Large area of corrosion, however none very deep | 3 |
| 61 | Manual | 0.75-in. | 1.4% | Medium | 6 | Some | 63% | Moderate | 26.5 | 28% | A few deep areas of corrosion. Significant amount of pipe with full wall thickness | 2 |

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[20] Not including Pipe 145/146, which was an incomplete pipe segment exhumed for comparison to external inspection results.

**Table 5-7. Echologics ThicknessFinder Condition Assessment Results for Eleven Destructively Assessed Pipes (Continued)**

| Pipe # | Method | ThicknessFinder Equivalent Thickness (Includes Coating) | Volume Loss | | Deep Pits >50% | Rating | Max. Pit Depth | Rating | Largest Patch | | Visual Assessment | Relative |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Percent | Relative | | | | | Length (in.) | Depth | | |
| 63 | Laser | 0.75-in. | 2.6% | Largest | 6 | Some | 51% | Moderate | 40 | 32% | Large areas of corrosion with moderate depth. Some pipe with full wall thickness | 1 |
| 64 | Laser | 0.75-in. | 2.1% | Largest | 5 | Some | 72% | Deep | 60 | 29% | Areas of corrosion with moderate depth and a few deep corrosion pits. Significant amount of pipe with full wall thickness. | 1 |
| 69 | Manual | 0.75. | 1.6% | Medium | 4 | Some | 75% | Deep | 14.5 | 33% | Moderate and a few deep pits, mostly in clusters. | 2 |
| 98 | Manual | 0.71-in. | 0.9% | Small | 1 | Very few | 63% | Moderate | 9.5 | 30% | Moderate pits, often in clusters. | 3 |
| 137 | Manual | 0.72 | 1.1% | Small | 0 | Very few | 46% | Moderate | 20 | 22% | Generally light corrosion. Clusters of shallow pits and large amount of pipe with full wall thickness. | 4 |
| 166 | Manual | 0.69-in. | 0.3% | Minimal | 0 | Very few | 37% | Not deep | 20 | 15% | Light corrosion and areas of pipe with full wall thickness. | 4 |

5.2.1 Sahara® Video. Sahara Video® presented the results of the video inspection as a sequence of observations. Three types of observations were reported: outlets (branch connections, hydrants, etc.), air pockets, and corrosion. EPA's contractor had no means to verify the presence of air pockets. However, one week prior, one of the leak detection systems noted that air pockets were present.

**Summary of Results.** The Sahara® Video inspection identified several visible features over the length of the test pipe. Two fairly large areas of internal corrosion were found at 1,565 ft and 1,637 ft. Additional air pockets, ranging from small to large in size, were also discovered during the video inspection. Details of these observations are presented in Table 5-8 with specific information on the direction and distance the observation was found from the insertion point (Pit 1).

**Table 5-8. Sahara Video Observation Details**

| No. | Description | Estimated Distance from Pit 1 (ft) | Direction from Insertion | Potential Correlated Pipe Feature |
|---|---|---|---|---|
| 1 | Outlet | 154 | Downstream | - |
| 2 | Outlet | 677 | Downstream | - |
| 3 | Air pocket | 886 | Downstream | - |
| 4 | Large air pocket | 1,024 | Downstream | - |
| 5 | Outlet | 1,061 | Downstream | Pit 2 (1,080 ft) |
| 6 | Large air pocket | 1,237 | Downstream | - |
| 7 | Outlet | 1,552 | Downstream | Pit 5 (1,580 ft) |
| 8 | Corrosion | 1,565 | Downstream | - |
| 9 | Outlet | 1,628 | Downstream | - |
| 10 | Large area of corrosion | 1,637 | Downstream | - |
| 11 | Outlet | 1,755 | Downstream | Pit F (1,750 ft) |
| 12 | Outlet | 1,946 | Downstream | - |

**Comparison to Assessed Pipe Samples.** Sahara Video® provided results for the entire pipe length used in the demonstration. EPA's contractor examined the cement lining using a CCTV crawler in the pipe after it was dewatered prior to excavation. In general, the CCTV revealed that the lining in the pipe was continuous without any missing areas, which compares well with what Sahara Video® reported. Due to a miscommunication with the excavation company, the two pipes with internal coating defects were scrapped before confirmation could be performed.

**Discussion.** Sahara Video® examined a segment of the interior circumference for the full length of the test pipe. Sahara Video® provided results that confirmed that the pipe lining was in generally good condition and had minimal degradation or delamination. Also, no debris or tuberculation was found in the pipe. This inspection was a valuable part of the demonstration as it was the first assessment of the ID of the pipe and provided some assurance that subsequent internal condition assessment methods could be successfully applied since an unobstructed path was available from one end of the pipe to the other.

5.2.2 PipeDiver®. PipeDiver® testing was conducted as early implementation of this technology. Data was analyzed and characterized based on basic pattern recognition from simple models of wall thickness variations. PipeDiver® could detect the start and end locations of pipe joints where anomalies were identified. Specific anomalies with metal loss or pitting were not identified.

**Summary of Results.** The PipeDiver® RFEC results showed joint signals, known features and anomalous signals, which were reportedly due to wall thickness loss. Table 5-9 lists the location of pipe sections that PipeDiver® data characterized as anomalous and their distance from the launch location in Pit 1. Forty-one of a total of 170 pipe segments showed anomalous signals; this was a detection methodology and sizing of the extent of degradation based on the signal was not performed. Of the anomalous pipe segments, 14 were identified in the first half of the test pipe, while 27 were identified in the second half of the test pipe. Further verification and calibration are needed by the inspection vendor to confirm the nature of these anomalous signals.

**Table 5-9. PipeDiver® Anomalous Pipes**

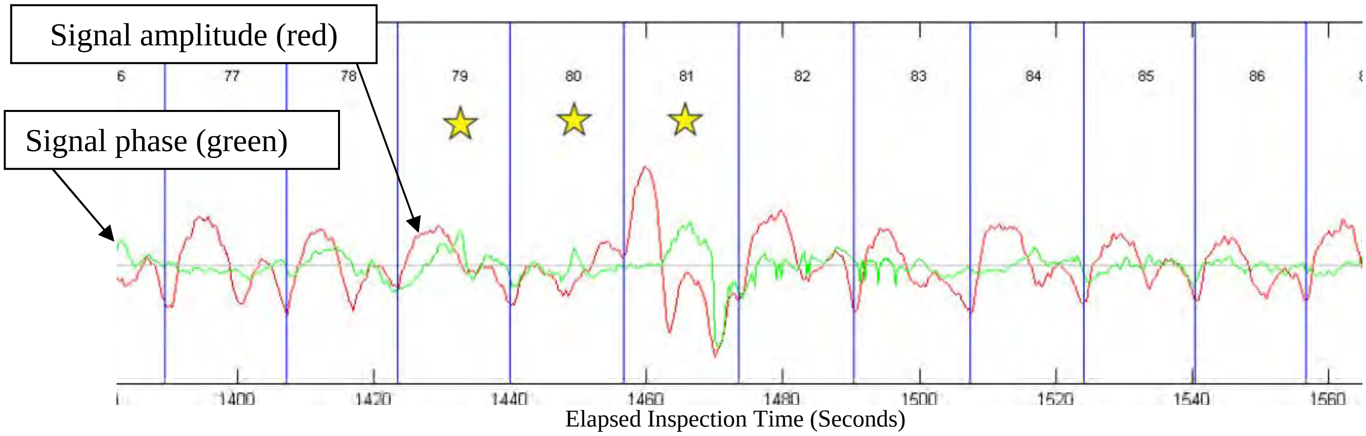
| Distance from Pit 1 (ft) | | | |
|---|---|---|---|
| **Start** | **End** | **Start** | **End** |
| 216 | 228 | 1,356 | 1,368 |
| 264 | 276 | 1,368 | 1,380 |
| 276 | 288 | 1,416 | 1,428 |
| 324 | 336 | 1,452 | 1,464 |
| 360 | 372 | 1,512 | 1,524 |
| 384 | 396 | 1,584 | 1,596 |
| 444 | 456 | 1,608 | 1,620 |
| 504 | 516 | 1,620 | 1,632 |
| 516 | 528 | 1,644 | 1,656 |
| 576 | 588 | 1,656 | 1,668 |
| 612 | 624 | 1,704 | 1,716 |
| 864 | 876 | 1,740 | 1,752 |
| 936 | 948 | 1,752 | 1,764 |
| 948 | 960 | 1,788 | 1,800 |
| 1,044 | 1,056 | 1,812 | 1,824 |
| 1,056 | 1,068 | 1,860 | 1,872 |
| 1,176 | 1,188 | 1,872 | 1,884 |
| 1,212 | 1,224 | 1,908 | 1,920 |
| 1,284 | 1,296 | 1,956 | 1,968 |
| 1,308 | 1,320 | 1,992 | 2,004 |
| 1,332 | 1,344 | - | - |

Figure 5-10 shows an example of several pipes classified as anomalous from their RFEC signal. The proprietary processing routine produced two separate outputs, signal amplitude (red curve) and signal phase (green curve). When assessing the red signal, the two hump pattern with the first higher than the second is considered normal. The entire signal in pipe 81 is larger and different from the normal pipe signal and could be due to wall thickness loss or from an unidentified pipe feature. Pipe 80 is missing the pattern altogether, which could be due to a wall thickness loss. For pipe 79, the dip is missing, but this may be due to degradation in pipe 80. The green signal was not useful in characterizing pipe.

Four manufactured defects were machined into Pit F on July 28th (see Figure 5-11). By comparing the RFEC signals from the data before and after the defects were created gave PipeDiver® data analysts the best possible chance of seeing the relatively small amount of wall thickness loss in the data (see Figure 5-12).

The PipeDiver® RFEC results showed good repeatability between multiple scans using the same configuration. The RFEC data showed joint signals, known features and anomalous signals that were attributed to wall thickness loss, but the results of this demonstration suggest that further calibration is needed to confirm the nature of these anomalous signals.

The detection and sizing sensitivity of PipeDiver® is limited by the number of sensor channels. As such, the inspection vendor reported that the future developments will focus on improving the detectors and their placement (including increasing the number of available detectors). In addition, the analysis process will be reviewed for new techniques and improved software. Specifications and implementations of the size and installation of hot taps for tool access will also be reviewed to prevent future insertion and retrieval issues.



(Courtesy of vendor)

**Figure 5-10. PipeDiver RFEC Anomalous Pipes (for Reference Elapsed Inspection Time (sec) and Pipe Length Number are Given)**

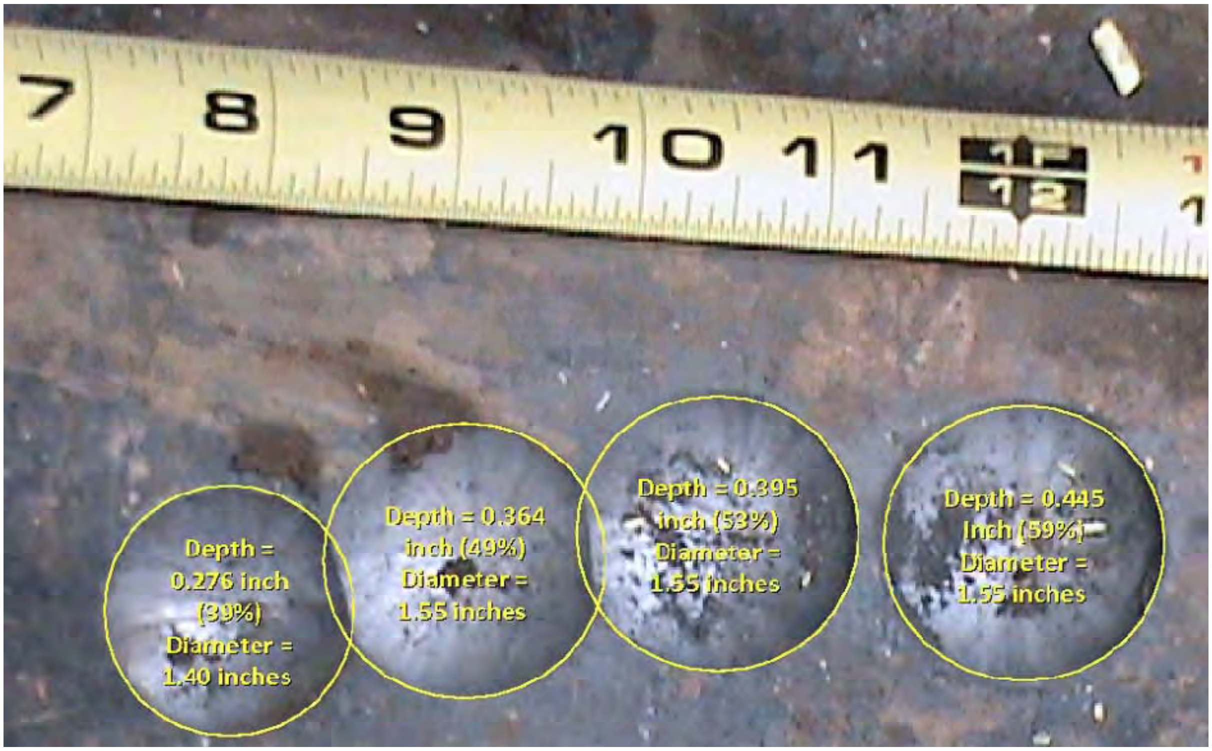
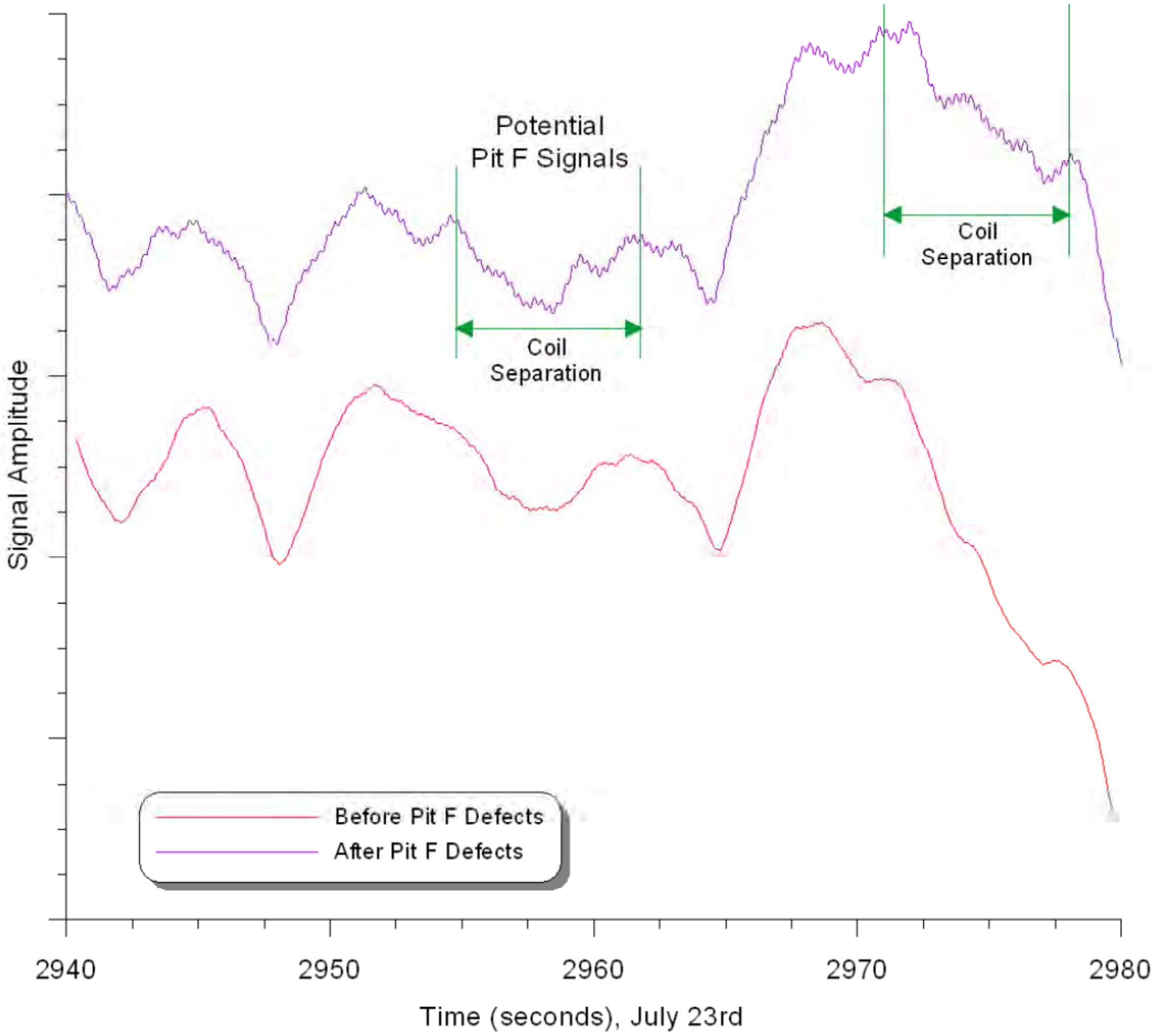


**Figure 5-11. Calibration Defects in Pit F**



(Courtesy of vendor)

**Figure 5-12. Comparing RFEC Data Before and After Defects**

**Comparison to Assessed Pipe Samples.** Forty-one of the 169 pipe lengths (24%) were identified by PipeDiver® as being anomalous. Twelve, 12-ft pipe lengths were characterized by EPA's contractor, and ranked on a 4 point scale with "1" being relatively more degraded and "4" being relatively least degraded. The results of the evaluations for 11 of these pipe lengths, for both PipeDiver® and for EPA's contractor, are in Table 5-10. PipeDiver® reported two of the 11 pipe lengths as anomalous. One pipe rated by EPA's contractors as being in the relatively most degraded category (i.e., "1"), with the most pits > 50% (13), the deepest pit (85% wall thickness), and the largest corrosion patch (25.2-in. long and 48% deep) was identified as anomalous by PipeDiver®. Two other pipes rated "1" were not determined anomalous by PipeDiver®. One of those pipes had large areas of corrosion with moderate depth and some pipe with full wall thickness; the other had areas of corrosion with moderate depth, a few deep corrosion pits, and a significant amount of pipe with full wall thickness. A second anomalous pipe identified by PipeDiver® was rated "2" by EPA's contractor, and it had a long corrosion area (22.5-in long; 35% depth) with a moderately deep (56%) corrosion pit in the center, and generally light corrosion elsewhere. Two other pipes rated "2" were not found anomalous by PipeDiver®. The remaining five pipes that showed minimal degradation, were rated "3" or "4", and were correctly identified as not degraded by PipeDiver®.

**Discussion.** The demonstration showed that a large in-line inspection tool could be launched and retrieved from an operating pipeline. This was the initial use of this technology on an operational cast iron water main. PipeDiver® provided results for the entire pipe length used in the demonstration. It successfully identified pipes independently determined to be in good condition. Due to the lack of test pipe sections with large areas of severe metal loss, its capability for identifying these types of pipes could not be demonstrated or evaluated. PipeDiver® results were mixed compared to the EPA contractor's assessment when attempting to discriminate between levels of degradation in pipe that was in overall good condition (i.e., $\leq$ 2.6 % overall wall loss). In those pipes, some substantial corrosion patches, deep corrosion pits, and up to 6 pits > 50% did not cause pipes to be reported as anomalous. This may or may not be a concern, depending on inspection goals and criteria. The technology capability could be evaluated and potentially improved with further calibration to a wider range of pipe excavation information from the field. This vehicle may prove to be a good platform for mounting sensors for condition assessment of cast iron and other pipes.

**Table 5-10. PPIC PipeDiver® Results for Eleven Destructively Assessed Pipes**[21]

| Pipe # | Method | PipeDiver® Anomalous Signals | Volume Loss | | Deep Pits >50% | Rating | Max. Pit Depth | Rating | Largest Patch | | Visual Assessment | Relative |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Percent | Relative | | | | | Length (in.) | Depth | | |
| 30 | Manual | no | 0.2% | Minimal | 1 | Very few | 68% | Deep | 5 | 26% | Generally light corrosion with one deep pit | 4 |
| 32 | Manual | yes | 0.7% | Small | 2 | Very few | 56% | Moderate | 22.5 | 35% | A long corrosion area with a moderately deep corrosion pit in the center. Generally light corrosion elsewhere. | 2 |
| 49 | Manual | yes | 1.0% | Small | 13 | Most | 85% | Deep | 25.2 | 48% | A 2 ft long corrosion area with many deep corrosion pits, one near through wall. Generally moderate corrosion elsewhere | 1 |
| 56 | Laser | no | 2.1% | Largest | 0 | Very few | 39% | Not deep | 60 | 22% | Large area of corrosion, however none very deep | 3 |
| 61 | Manual | no | 1.4% | Medium | 6 | Some | 63% | Moderate | 26.5 | 28% | A few deep areas of corrosion. Significant amount of pipe with full wall thickness | 2 |
| 63 | Laser | no | 2.6% | Largest | 6 | Some | 51% | Moderate | 40 | 32% | Large areas of corrosion with moderate depth. Some pipe with full wall thickness | 1 |

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[21] Not including Pipe 145/146, which was an incomplete pipe segment exhumed for comparison to external inspection results.

| Pipe # | Method | PipeDiver® Anomalous Signals | Volume Loss | | Deep Pits >50% | Rating | Max. Pit Depth | Rating | Largest Patch | | Visual Assessment | Relative |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Percent | Relative | | | | | Length (in.) | Depth | | |
| 64 | Laser | no | 2.1% | Largest | 5 | Some | 72% | Deep | 60 | 29% | Areas of corrosion with moderate depth and a few deep corrosion pits. Significant amount of pipe with full wall thickness | 1 |
| 69 | Manual | no | 1.6% | Medium | 4 | Some | 75% | Deep | 14.5 | 33% | Moderate and a few deep pits, mostly in clusters. | 2 |
| 98 | Manual | no | 0.9% | Small | 1 | Very few | 63% | Moderate | 9.5 | 30% | Moderate pits, often in clusters. | 3 |
| 137 | Manual | no | 1.1% | Small | 0 | Very few | 46% | Moderate | 20 | 22% | Generally light corrosion. Clusters of shallow pits and large amount of pipe with full wall thickness. | 4 |
| 166 | Manual | no | 0.3% | Minimal | 0 | Very few | 37% | Not deep | 20 | 15% | Light corrosion and areas of pipe with full wall thickness. | 4 |

### 5.2.3 See Snake®.

See Snake® collected data over the entire pipe length and reported bell and spigot joints, pipeline features such as tees, and metal loss anomalies. For the metal loss anomalies, the maximum extent, axial distance, and clock position was provided. For many pipe segments, no metal loss anomalies were reported, while other pipe segments had multiple anomalies. The report also provided a summary of the results, which gave a quick overview of the condition of the pipe.

**Summary of Results.** The tabulated results provided by the vendor indicated all verified ball and socket joints were detected. Some other large signals were also observed, but they could not always be correlated back to observable or known features such as hydrants and tees, and were assumed to be metal loss anomalies. Valves and tee branches were accurately located by See Snake®. The following was noted:

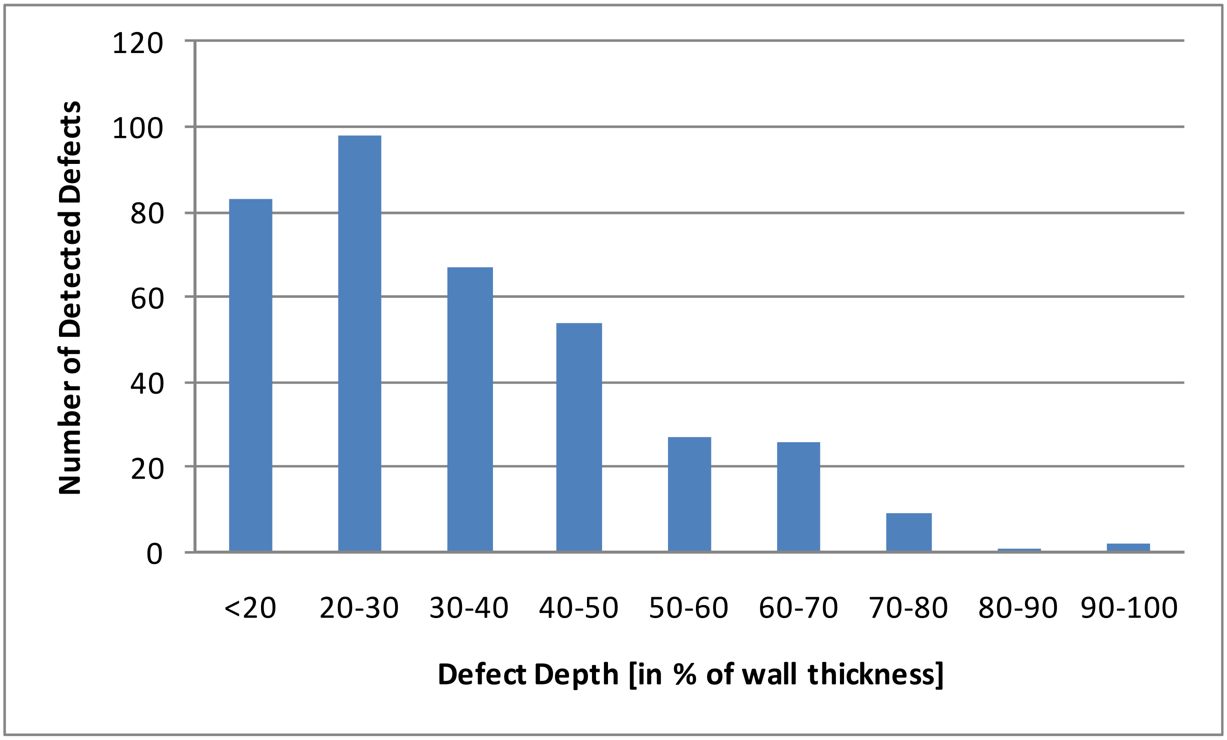
- 12.2 ft pipe lengths were common throughout the line.
- A number of major line features were noticed in the data, which are believed to be two valves and two branches.

The inspection of the water line resulted in 367 wall loss indications. A histogram of the results shows that a majority of the defects were less than or equal to 50% deep, with a much smaller group in the 60-80% range, and only a few defects 90% or deeper. More importantly, the results from the See Snake® tool show that the deep defects are concentrated within the first half of the line, leaving about half the line in relatively good shape. A histogram of the number of defects by wall loss percentage is provided in Figure 5-13, while the defect depth as a function of distance along the pipeline is provided in Figure 5-14.

The vendor reported that due to magnetic permeability noise, See Snake® was not able to characterize any of the machined calibration pits or test pits. Four potential causes of the noise were identified by the vendor: (1) insufficient coolant when drilling the pits may have caused heating and stresses that changed magnetic permeability; (2) a magnetic base on the drilling machine may have affected magnetic permeability; (3) use of other inspection devices with permanent magnets for attaching to the pipe; and, (4) use of technologies that saturated the pipe with a magnetic field. Therefore, the vendor calibrated their device with their own test samples.

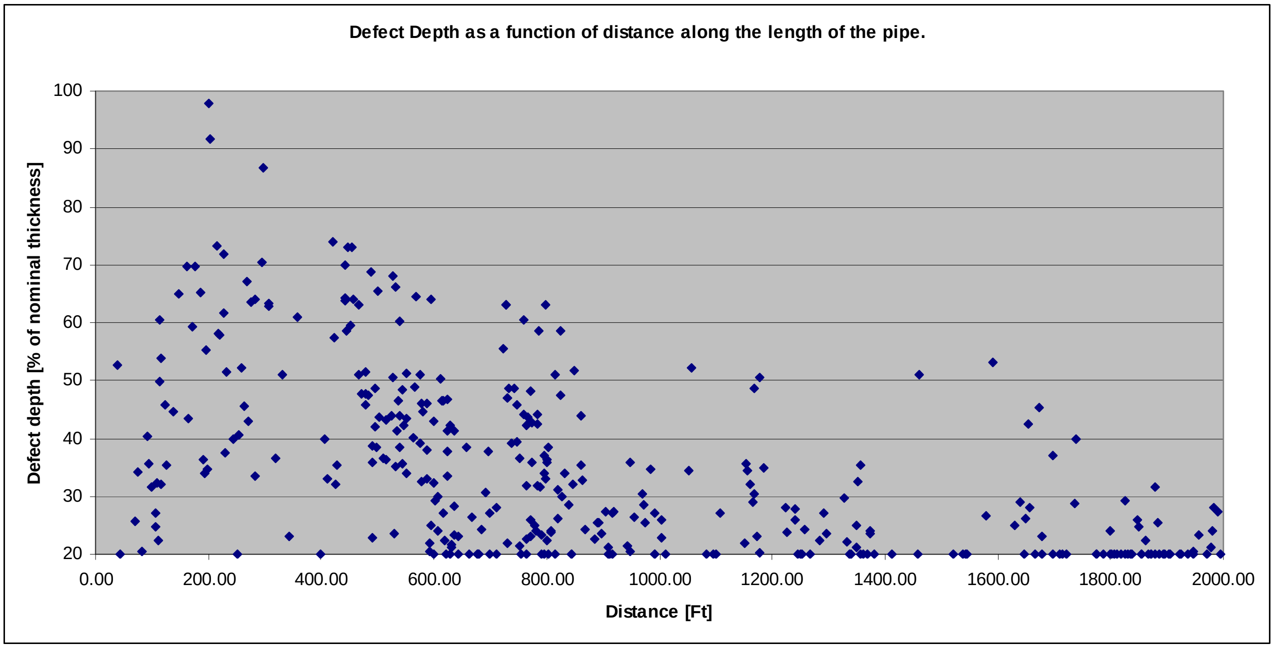
**Comparison to Assessed Pipe Samples.** See Snake® provided detailed results for the entire pipe length examined in the demonstration. The comparison of results is provided in Table 5-11. Of the eleven pipes that underwent detailed examinations, the pipes with the largest number of metal loss indications were also reported by See Snake® to have a large number of pits. The number of pits may not be an exact measure because deciding whether a corrosion area is two pits or one larger pit is not always possible. Additionally, the pipes that showed minimal degradation in the detailed examinations were also correctly identified by See Snake® as having few or small anomalies.

**Discussion.** Of all of the condition assessment technologies demonstrated, See Snake® provided the most detailed results for the entire pipe length and correlated the best with the post-demonstration assessment of the exhumed pipe segments. The total number of corrosion pits, as well as corrosion pit location with respect to the pipe joint and clock position, were clearly reported and correlate well. This was the initial use of this tool and the last technology demonstrated. Since replacement of the line was scheduled to begin immediately following the demonstration, there was not time for additional tests or slips in the schedule. There was trouble controlling the winch that caused velocity excursions, jerking and surging. On the final day, all equipment worked well and an acceptable data set was acquired. The implementation was intrusive for the demonstration as the pipe had to be drained and cut, and a pull cable had to be threaded for this inspection. The potential for magnetic interference and its potential effects on See Snake® performance should be considered during future testing and/or application of the technology.



(Adapted from vendor report)

**Figure 5-13. See Snake® Defect Histogram**



(Courtesy of vendor report)

**Figure 5-14. See Snake® Defect Scatter Graph**

## Table 5-11. See Snake® Results for Eleven Destructively Assessed Pipes[1]

| Pipe # | Method | See Snake® Pit Assessment [% of wall thickness] | Volume Loss | | Deep Pits >50 % | | Max Pit Depth | | Largest Patch | | Visual Assessment | Relative |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Percent | Relative | | Rating | | Rating | Length (in.) | Depth | | |
| 30 | Manual | 1 pit [at about 60%] | 0.2% | Minimal | 1 | Very few | 68% | Deep | 5 | 26% | Generally light corrosion with one deep pit. | 4 |
| 32 | Manual | 0 | 0.7% | Small | 2 | Very few | 56% | Moderate | 22.5 | 35% | A long corrosion area with a moderately deep corrosion pit in the center. Generally light corrosion elsewhere. | 2 |
| 49 | Manual | 7 reported, [2 greater than 40%] | 1.0% | Small | 13 | Most | 85% | Deep | 25.2 | 48% | A 2 ft long corrosion area with many deep corrosion pits, one near through wall. Generally moderate corrosion elsewhere | 1 |
| 56 | Laser | 4 reported, [all less than 20%] | 2.1% | Largest | 0 | Very few | 39% | Not deep | 60 | 22% | Large area of corrosion, however none very deep. | 3 |
| 61 | Manual | 3 reported, [2 greater than 40%] | 1.4% | Medium | 6 | Some | 63% | Moderate | 26.5 | 28% | A few deep areas of corrosion. Significant amount of pipe with full wall thickness. | 2 |
| 63 | Laser | 7 reported, [4 greater than 40%] | 2.6% | Largest | 6 | Some | 51% | Moderate | 40 | 32% | Large areas of corrosion with moderate depth. Some pipe with full wall thickness. | 1 |
| 64 | Laser | 6 reported, [2 greater than 40%] | 2.1% | Largest | 5 | Some | 72% | Deep | 60 | 29% | Areas of corrosion with moderate depth and a few deep corrosion pits. | 1 |

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[1] Not including Pipe 145/146, which was an incomplete pipe segment exhumed for comparison to external inspection results.

| Pipe # | Method | See Snake® Pit Assessment [% of wall thickness] | Volume Loss | | Deep Pits >50 % | | Max Pit Depth | | Largest Patch | | Visual Assessment | Relative |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Percent | Relative | | Rating | | Rating | Length (in.) | Depth | | |
| | | | | | | | | | | | Significant amount of pipe with full wall thickness. | |
| 69 | Manual | 2 reported on the order of 30% | 1.6% | Medium | 4 | Some | 75% | Deep | 14.5 | 33% | Moderate and a few deep pits, mostly in clusters. | 2 |
| 98 | Manual | 1 pit at about 35% | 0.9% | Small | 1 | Very few | 63% | Moderate | 9.5 | 30% | Moderate pits, often in clusters | 3 |
| 137 | Manual | 1 pit at about 35% | 1.1% | Small | 0 | Very few | 46% | Moderate | 20 | 22% | Generally light corrosion. Clusters of shallow pits and large amount of pipe with full wall thickness | 4 |
| 166 | Manual | 1 small pit | 0.3% | Minimal | 0 | Very few | 37% | Not deep | 20 | 15% | Light corrosion and areas of pipe with full wall thickness | 4 |

## 5.3. External Assessment

The AESL ECAT, RSG HSK and RSG CAP external inspection technologies were demonstrated on the same cast iron water main in Louisville, KY as described above.

- AESL attaches the ECAT system to the exterior of the pipe using high strength magnets. The ECAT is manually operated at a small number of excavations along the pipeline, and uses MFL technology to locate and size defects. ECAT only scans a portion of the exposed pipe at one time and then must be repositioned. This process continues until the entire circumference and length of the exposed pipe has been scanned. The data from the ECAT system is used in combination with data from commercial ultrasonic instruments, visual inspection of coating condition, soil properties, and traffic loads to statistically predict the condition of long lengths of un-inspected pipe.
- RSG HSK is a handheld device that uses a patented BEM technology to assess the localized pipeline condition in select excavations. The HSK is manually moved around the exposed pipe in a grid pattern to collect pipe defect data (remaining wall thickness, areas of metal loss, and fractures). The HSK system is designed to scan along the length and diameter of the pipe.
- RSG CAP also uses the BEM technology, but is for keyhole inspections. The device operates with a down-hole, clamp-on device to affix the sensors to the pipe. The CAP system is only designed to scan the top portion of the pipe exposed via the keyhole excavation. Capability for full circumference scans via a keyhole is now reportedly available .

Each external condition assessment tool found a large number of anomalies in the excavated pipeline sections that underwent inspection. Verification of all anomalies is not practical; however some comparisons were attempted using the location and size of the machined defects with the results provided by each inspection vendor.

In particular, the corrosion sizing results for AESL ECAT were plotted in a manner commonly used by pipeline inspection vendors to demonstrate commercial inspection technology capabilities. For these graphs, benchmark data is plotted against the values reported by the technology developers. Care must be taken in interpreting these graphs since:

- Error in the destructive measurements is not zero.
- Grit blasting can remove good metal when attempting to remove deep graphitization. Also, the blasting process may not remove all of the corrosion or graphitization products.
- Only the maximum depth is compared, while the corrosion pit depth varied throughout the defect; many corrosion areas had more than one area of local thinning.
- Length and width were measured at the surface; however other measures can also be used that still accurately describes the anomaly such as volume divided by maximum depth.

Overall these graphs show the results predicted by AESL correlated well with the machined defect benchmark data. The same comparison charts could not be used to verify the results provided by RSG. As discussed previously, RSG only provides relative wall thinning data averaged over the sensor area (1x1-in. for CAP and 2x2-in. for HSK) and therefore does not offer the sensitivity needed to make a direct comparison with the machined defect data. Only general comments can be made based on the CAP and RSK devices regarding possible increased wall thinning in the location of the machined defects.

In addition, AESL provided soil and wall thickness analyses that were integrated with the condition assessment results to perform a statistical analysis of the condition of the uninspected portion of the pipeline.

### 5.3.1 AESL ECAT

**Summary of Results.** AESL took soil measurements including resistivity, redox, pipe-to-soil potential, and pH at 10 accessible locations along the pipeline (Pits A-F, Pits 1-3, and Pit L). Results from the soil survey were used to calculate a soil corrosivity score according to the French Standard AFNOR A05-250. These results are presented in Table 5-12.

**Table 5-12. Soil Corrosivity Results**

| Excavation Pit | AFNOR Score | Soil Corrosivity |
|---|---|---|
| Pit 1 | 6 | Fairly Corrosive |
| Pit A | 6 | Fairly Corrosive |
| Pit L | 7 | Fairly Corrosive |
| Pit B | 5 | Fairly Corrosive |
| Pit C | 8 | Highly Corrosive |
| Pit 2 | 5 | Fairly Corrosive |
| Pit D | 6 | Fairly Corrosive |
| Pit E | 6 | Fairly Corrosive |
| Pit F | 9 | Highly Corrosive |
| Pit 3 | 7 | Fairly Corrosive |

AESL also conducted, at pits F, 2, and L, visual inspections of the bitumen paint coating on the external surface of the pipeline. The general condition of the coating for each excavation as reported by AESL is provided in Figure 5-15 through Figure 5-17 as the percentage of failed coating per 0.1 m (3.9 in.) at regular intervals (16-degree) around the pipe circumference. Pit F and Pit L showed the least amount of coating failure with overall failure percentages of 11-percent and 6-percent, respectively. An area of coating at Pit F was in poor condition between 170-degrees and 280-degrees. Pit 2 exhibited the most failed coating with an overall failure percentage of 70-percent and several specific locations showing 100-percent coating failure.

AESL conducted a detailed pipe wall condition assessment using the ECAT for Pit F, Pit 2, and Pit L over a 1 m length and full pipe circumference. Table 5-13 summarizes the condition assessment results for the three excavation pits. The vast majority of the defects were external (~ 800), but ~ 23 internal defects were identified. The internal and external defects were differentiated with a proximity sensor. Some mechanical damage was also identified in Pits F and L. Figure 5-18 through Figure 5-21 graphically depict the size and location of specific metal loss defects. Because of the sheer number of defects identified in each excavation location only the 20 largest defects are presented in the figures. AESL also determined wall thickness with an ultrasonic device. The wall thickness for all three excavation locations ranged from a minimum of 17.6 mm (0.69 in.) to a maximum of 20.8 mm (0.82 in.).

**Table 5-13. Summarized Condition Assessment Results for Pit F, Pit 2, and Pit L**

| Excavation Pit | Summarized Condition Assessment Results |
|---|---|
| Pit F | ∗ ~240 external defects (largest was 0.43-in. depth)<br>∗ ~9 internal defects (largest was 0.39-in. depth)<br>∗ Mechanical damage between 180° and 270°; likely not to have occurred recently |
| Pit 2 | ∗ ~225 external defects (largest was 0.59-in. depth)<br>∗ ~11 internal defects (largest was 0.41-in. depth) |
| Pit L | ∗ ~330 external defects (largest was 0.57-in. depth)<br>∗ ~3 internal defects (largest was 0.41-in. depth)<br>∗ Mechanical damage at ~90° and between 180° and 280° |

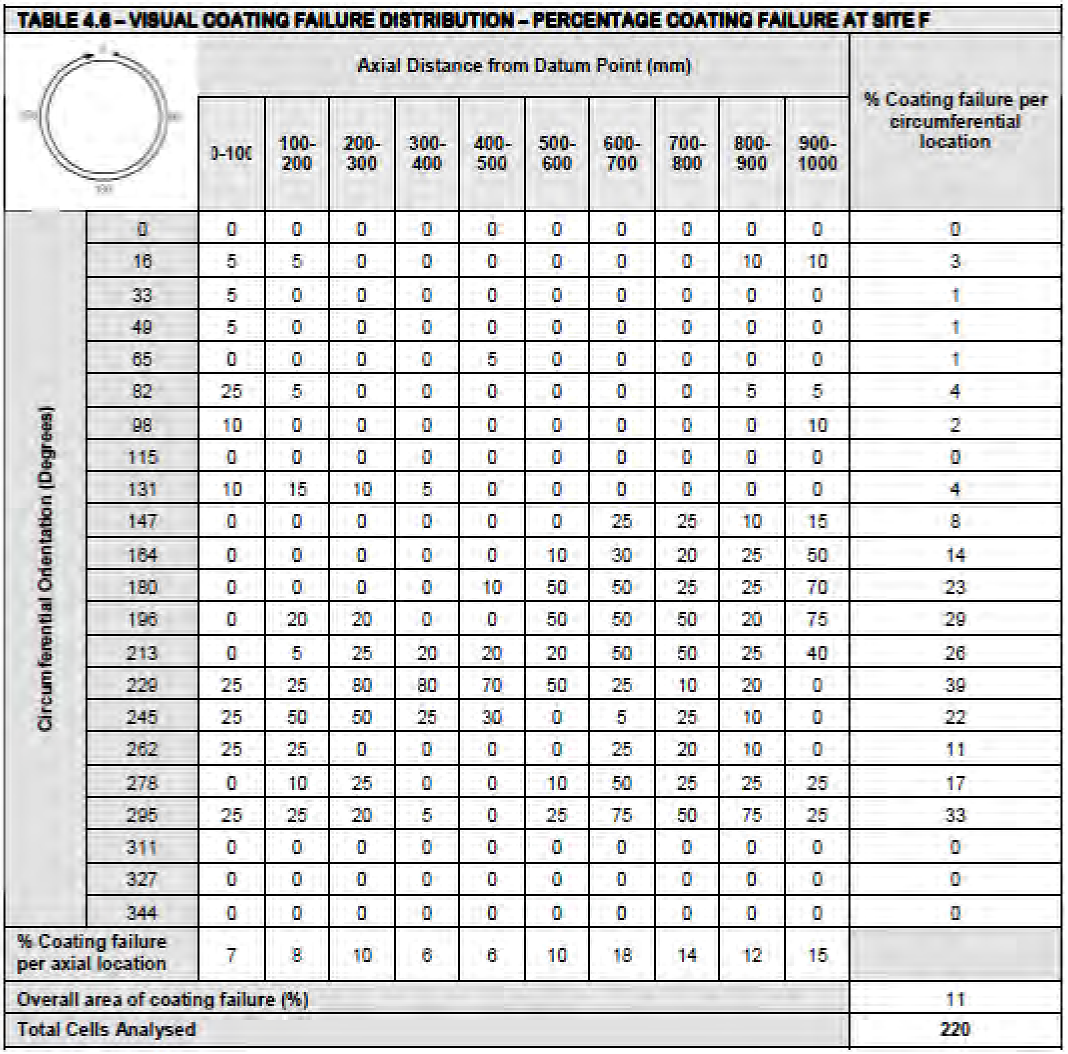


**TABLE 4.6 – VISUAL COATING FAILURE DISTRIBUTION – PERCENTAGE COATING FAILURE AT SITE F**

| | Axial Distance from Datum Point (mm) | | | | | | | | | | % Coating failure per circumferential location |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Circumferential Orientation (Degrees) | 0-10 | 100-200 | 200-300 | 300-400 | 400-500 | 500-600 | 600-700 | 700-800 | 800-900 | 900-1000 | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 5 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 10 | 3 |
| 33 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 49 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 65 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 1 |
| 82 | 25 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 4 |
| 98 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 2 |
| 115 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 131 | 10 | 15 | 10 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| 147 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 25 | 10 | 15 | 8 |
| 164 | 0 | 0 | 0 | 0 | 0 | 10 | 30 | 20 | 25 | 50 | 14 |
| 180 | 0 | 0 | 0 | 0 | 10 | 50 | 50 | 25 | 25 | 70 | 23 |
| 196 | 0 | 20 | 20 | 0 | 0 | 50 | 50 | 50 | 20 | 75 | 29 |
| 213 | 0 | 5 | 25 | 20 | 20 | 20 | 50 | 50 | 25 | 40 | 26 |
| 229 | 25 | 25 | 80 | 80 | 70 | 50 | 25 | 10 | 20 | 0 | 39 |
| 245 | 25 | 50 | 50 | 25 | 30 | 0 | 5 | 25 | 10 | 0 | 22 |
| 262 | 25 | 25 | 0 | 0 | 0 | 0 | 25 | 20 | 10 | 0 | 11 |
| 278 | 0 | 10 | 25 | 0 | 0 | 10 | 50 | 25 | 25 | 25 | 17 |
| 295 | 25 | 25 | 20 | 5 | 0 | 25 | 75 | 50 | 75 | 25 | 33 |
| 311 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 327 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 344 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| % Coating failure per axial location | 7 | 8 | 10 | 6 | 6 | 10 | 18 | 14 | 12 | 15 | |
| Overall area of coating failure (%) | | | | | | | | | | | 11 |
| Total Cells Analysed | | | | | | | | | | | 220 |

(Courtesy of AESL)

**Figure 5-15. Visual Coating Failure Distribution – Pit F**

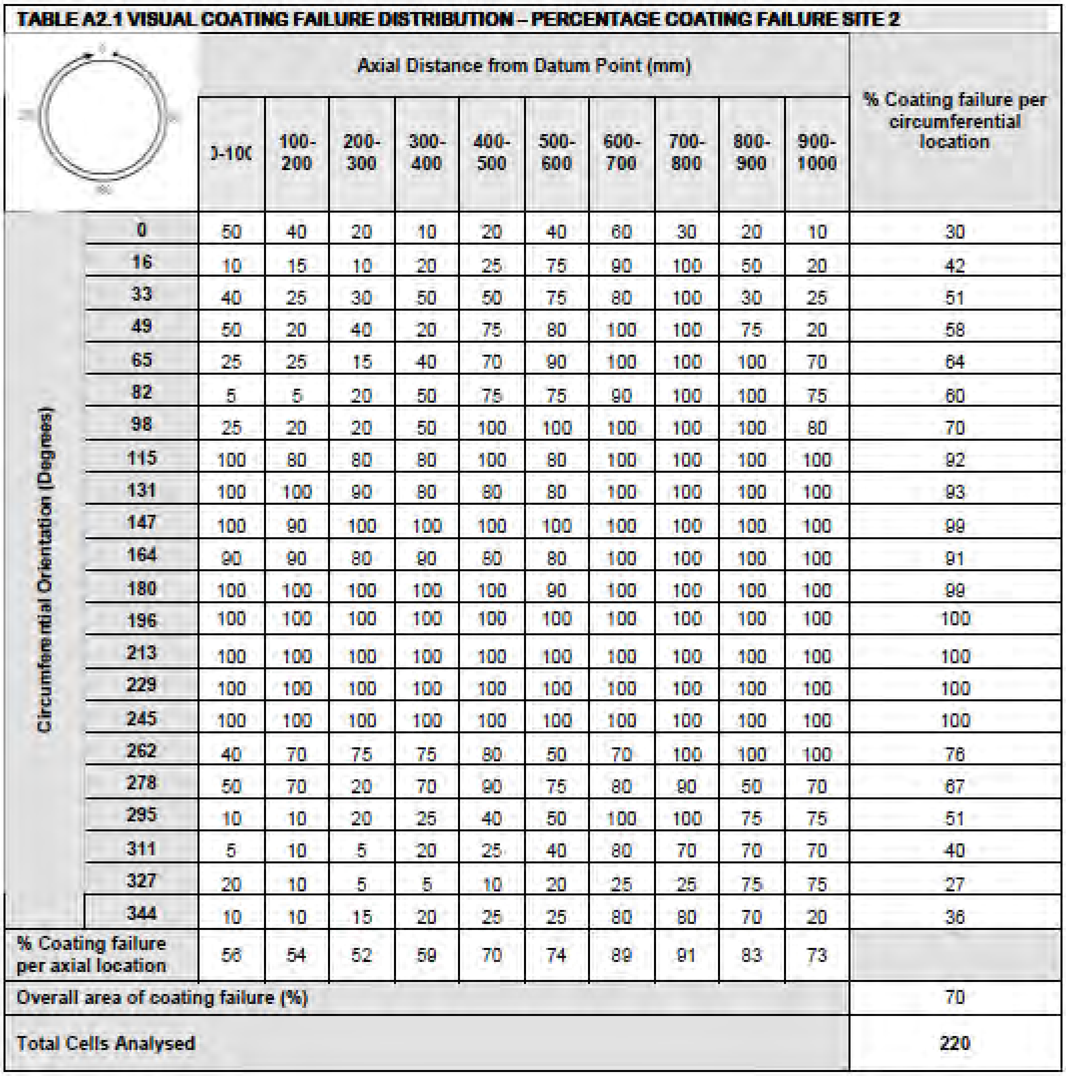


**TABLE A2.1 VISUAL COATING FAILURE DISTRIBUTION – PERCENTAGE COATING FAILURE SITE 2**

| | | Axial Distance from Datum Point (mm) | | | | | | | | | | % Coating failure per circumferential location |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | )-10( | 100-200 | 200-300 | 300-400 | 400-500 | 500-600 | 600-700 | 700-800 | 800-900 | 900-1000 | |
| Circumferential Orientation (Degrees) | 0 | 50 | 40 | 20 | 10 | 20 | 40 | 60 | 30 | 20 | 10 | 30 |
| | 16 | 10 | 15 | 10 | 20 | 25 | 75 | 90 | 100 | 50 | 20 | 42 |
| | 33 | 40 | 25 | 30 | 50 | 50 | 75 | 80 | 100 | 30 | 25 | 51 |
| | 49 | 50 | 20 | 40 | 20 | 75 | 80 | 100 | 100 | 75 | 20 | 58 |
| | 65 | 25 | 25 | 15 | 40 | 70 | 90 | 100 | 100 | 100 | 70 | 64 |
| | 82 | 5 | 5 | 20 | 50 | 75 | 75 | 90 | 100 | 100 | 75 | 60 |
| | 98 | 25 | 20 | 20 | 50 | 100 | 100 | 100 | 100 | 100 | 80 | 70 |
| | 115 | 100 | 80 | 80 | 80 | 100 | 80 | 100 | 100 | 100 | 100 | 92 |
| | 131 | 100 | 100 | 90 | 80 | 80 | 80 | 100 | 100 | 100 | 100 | 93 |
| | 147 | 100 | 90 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 |
| | 164 | 90 | 90 | 80 | 90 | 80 | 80 | 100 | 100 | 100 | 100 | 91 |
| | 180 | 100 | 100 | 100 | 100 | 100 | 90 | 100 | 100 | 100 | 100 | 99 |
| | 196 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | 213 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | 229 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | 245 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | 262 | 40 | 70 | 75 | 75 | 80 | 50 | 70 | 100 | 100 | 100 | 76 |
| | 278 | 50 | 70 | 20 | 70 | 90 | 75 | 80 | 90 | 50 | 70 | 67 |
| | 295 | 10 | 10 | 20 | 25 | 40 | 50 | 100 | 100 | 75 | 75 | 51 |
| | 311 | 5 | 10 | 5 | 20 | 25 | 40 | 80 | 70 | 70 | 70 | 40 |
| | 327 | 20 | 10 | 5 | 5 | 10 | 20 | 25 | 25 | 75 | 75 | 27 |
| | 344 | 10 | 10 | 15 | 20 | 25 | 25 | 80 | 80 | 70 | 20 | 36 |
| % Coating failure per axial location | | 56 | 54 | 52 | 59 | 70 | 74 | 89 | 91 | 83 | 73 | |
| Overall area of coating failure (%) | | | | | | | | | | | | 70 |
| Total Cells Analysed | | | | | | | | | | | | 220 |

(Courtesy of AESL)

Figure 5-16. Visual Coating Failure Distribution – Pit 2

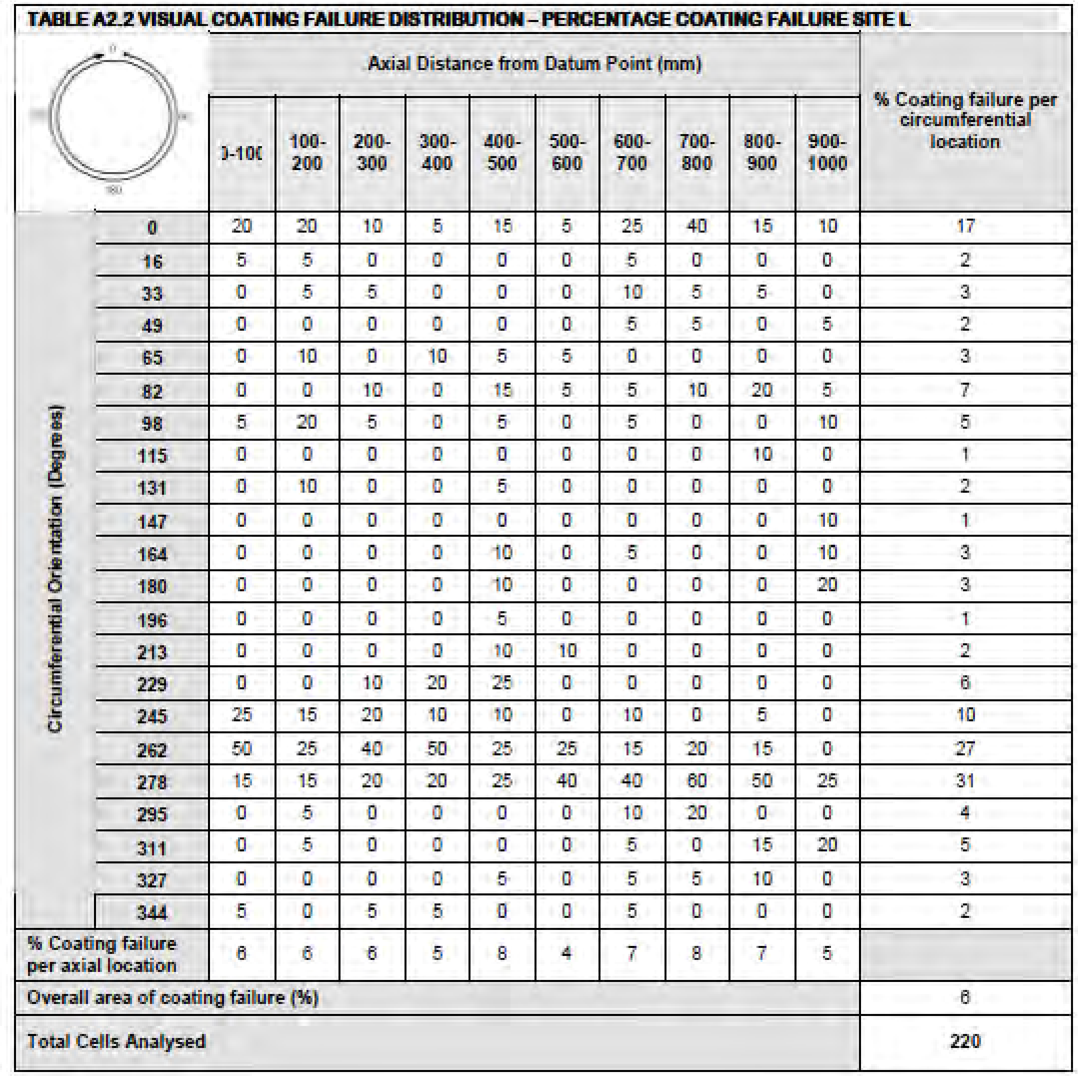
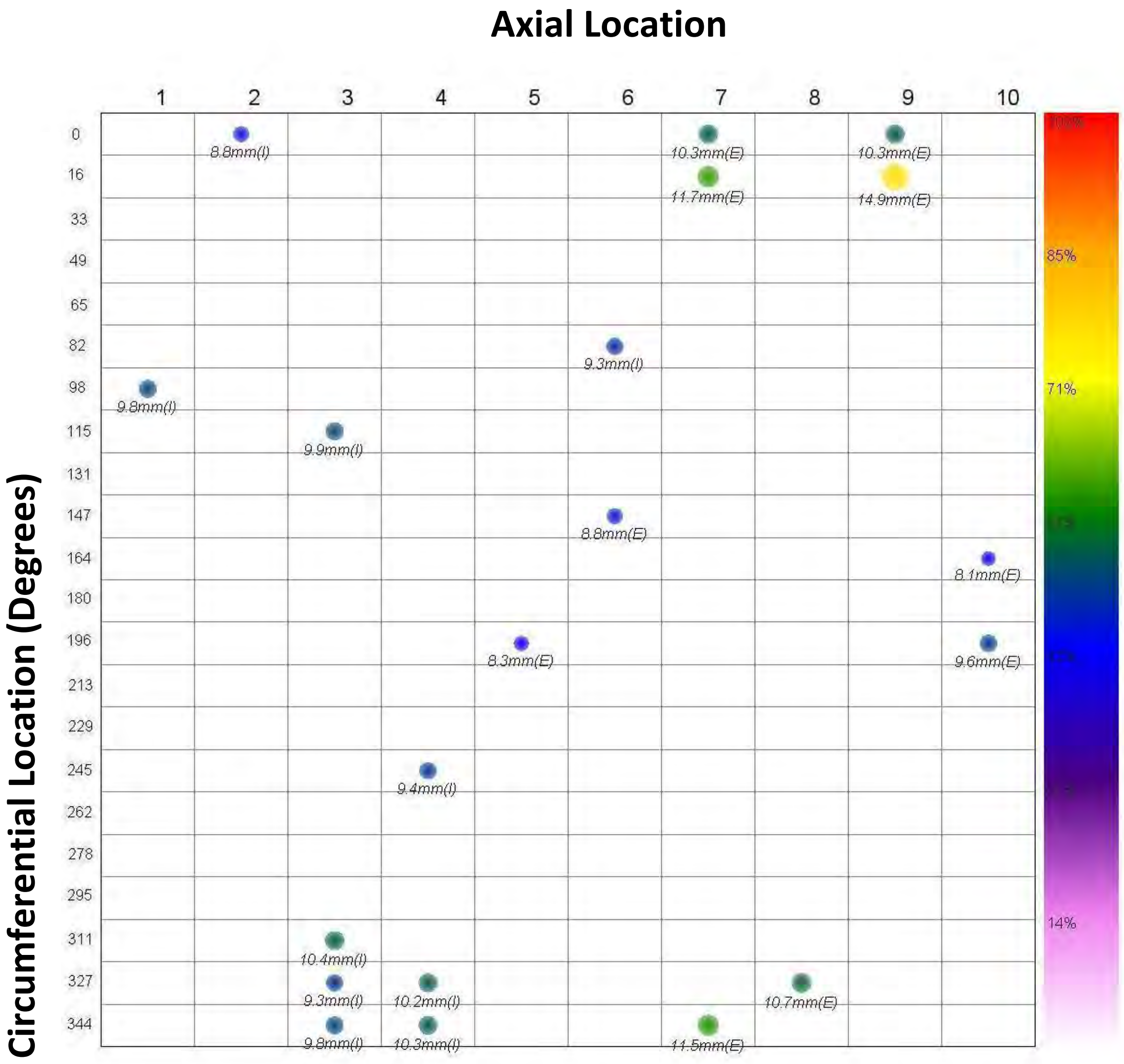


TABLE A2.2 VISUAL COATING FAILURE DISTRIBUTION – PERCENTAGE COATING FAILURE SITE L

| | | Axial Distance from Datum Point (mm) | | | | | | | | | | % Coating failure per circumferential location |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -10 | 100-200 | 200-300 | 300-400 | 400-500 | 500-600 | 600-700 | 700-800 | 800-900 | 900-1000 | |
| Circumferential Orientation (Degrees) | 0 | 20 | 20 | 10 | 5 | 15 | 5 | 25 | 40 | 15 | 10 | 17 |
| | 16 | 5 | 5 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 2 |
| | 33 | 0 | 5 | 5 | 0 | 0 | 0 | 10 | 5 | 5 | 0 | 3 |
| | 49 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 0 | 5 | 2 |
| | 65 | 0 | 10 | 0 | 10 | 5 | 5 | 0 | 0 | 0 | 0 | 3 |
| | 82 | 0 | 0 | 10 | 0 | 15 | 5 | 5 | 10 | 20 | 5 | 7 |
| | 98 | 5 | 20 | 5 | 0 | 5 | 0 | 5 | 0 | 0 | 10 | 5 |
| | 115 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 1 |
| | 131 | 0 | 10 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 2 |
| | 147 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 1 |
| | 164 | 0 | 0 | 0 | 0 | 10 | 0 | 5 | 0 | 0 | 10 | 3 |
| | 180 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 20 | 3 |
| | 196 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 213 | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 0 | 0 | 0 | 2 |
| | 229 | 0 | 0 | 10 | 20 | 25 | 0 | 0 | 0 | 0 | 0 | 6 |
| | 245 | 25 | 15 | 20 | 10 | 10 | 0 | 10 | 0 | 5 | 0 | 10 |
| | 262 | 50 | 25 | 40 | 50 | 25 | 25 | 15 | 20 | 15 | 0 | 27 |
| | 278 | 15 | 15 | 20 | 20 | 25 | 40 | 40 | 60 | 50 | 25 | 31 |
| | 295 | 0 | 5 | 0 | 0 | 0 | 0 | 10 | 20 | 0 | 0 | 4 |
| | 311 | 0 | 5 | 0 | 0 | 0 | 0 | 5 | 0 | 15 | 20 | 5 |
| | 327 | 0 | 0 | 0 | 0 | 5 | 0 | 5 | 5 | 10 | 0 | 3 |
| | 344 | 5 | 0 | 5 | 5 | 0 | 0 | 5 | 0 | 0 | 0 | 2 |
| % Coating failure per axial location | | 6 | 6 | 6 | 5 | 8 | 4 | 7 | 8 | 7 | 5 | |
| Overall area of coating failure (%) | | | | | | | | | | | | 6 |
| Total Cells Analysed | | | | | | | | | | | | 220 |

(Courtesy of AESL)

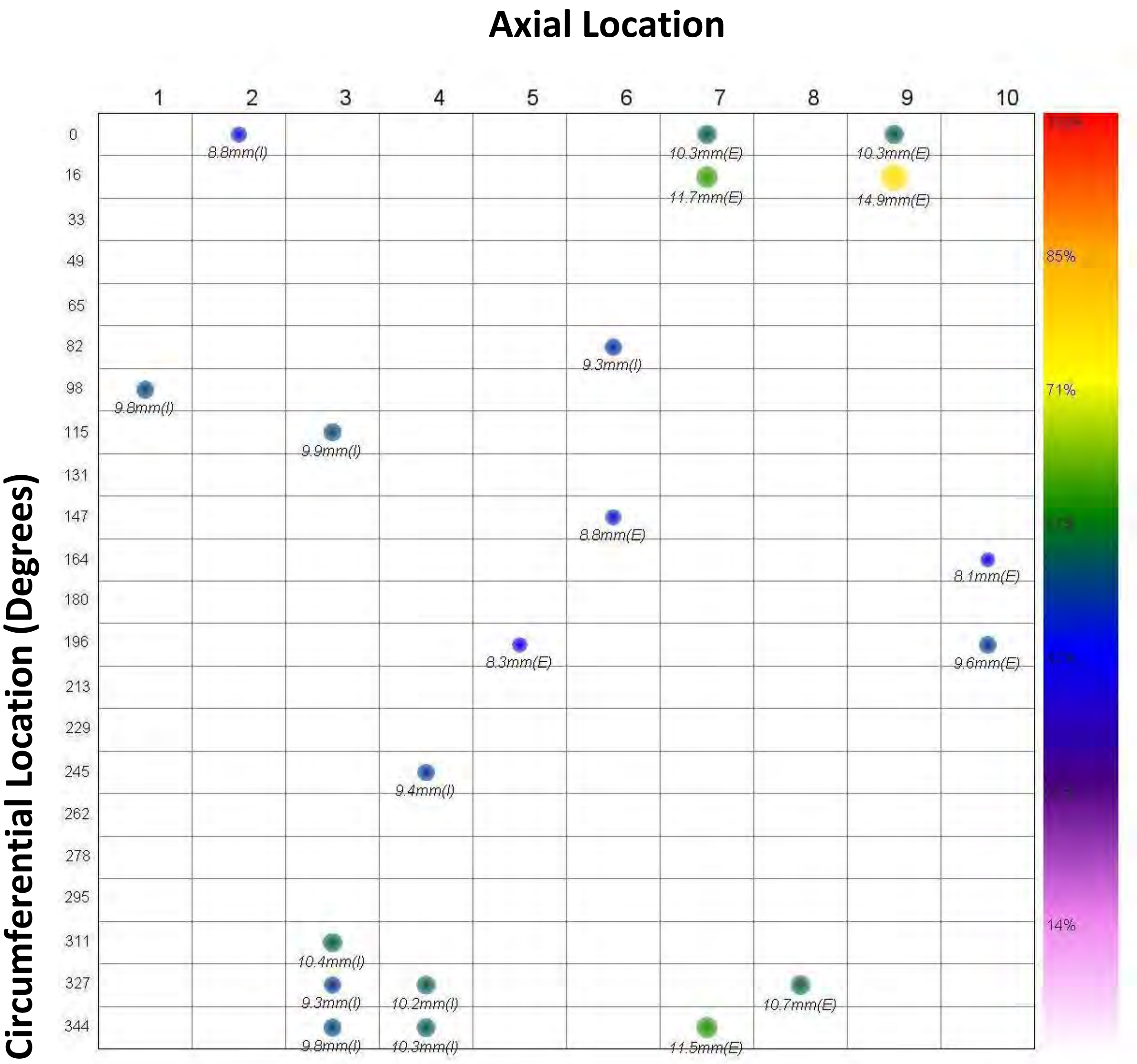
Figure 5-17. Visual Coating Failure Distribution – Pit L



E = external
I = internal

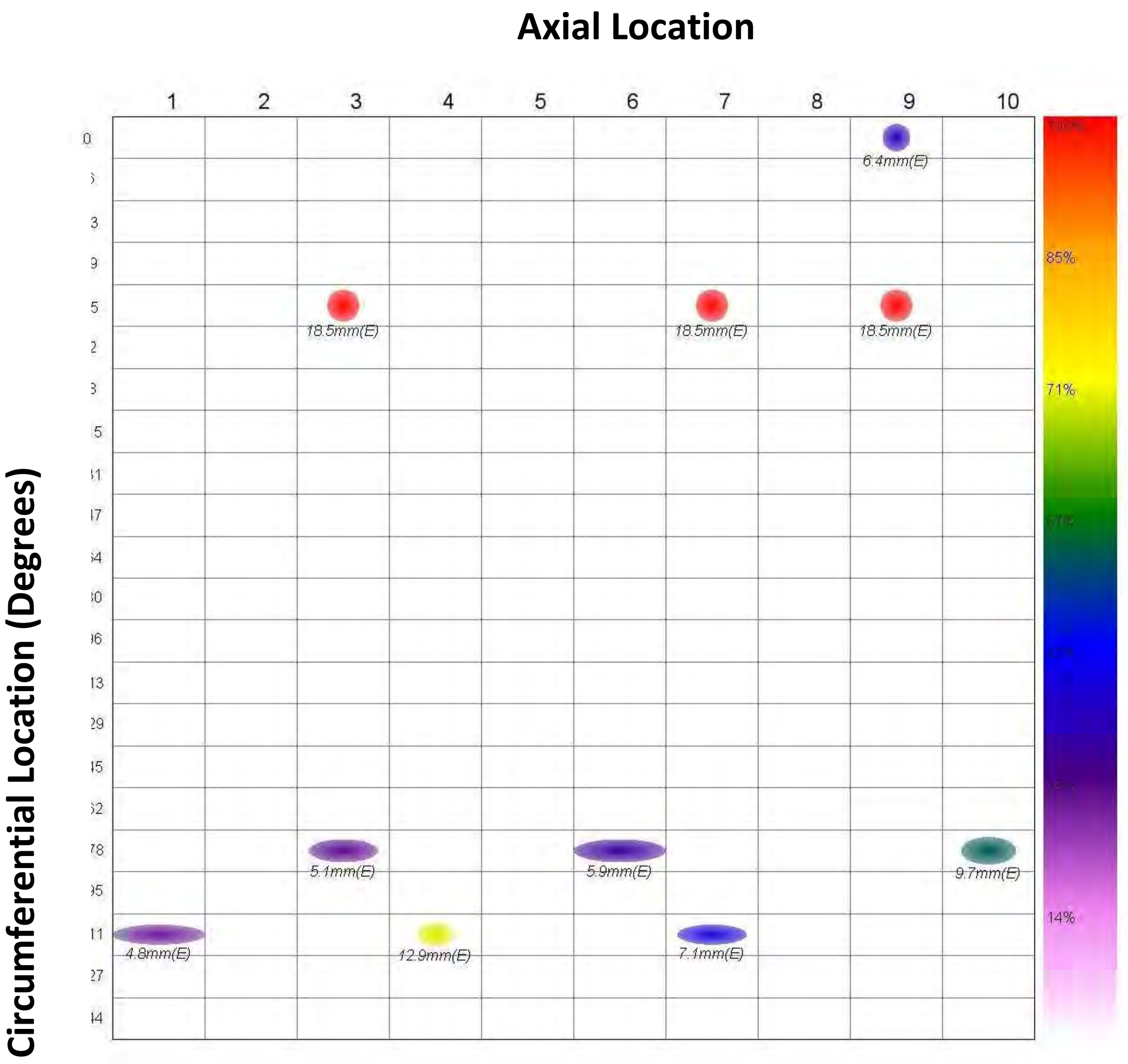
(Courtesy of AESL)

Figure 5-19. Defect Plot for Pit 2 (20 Largest Defect Depths)



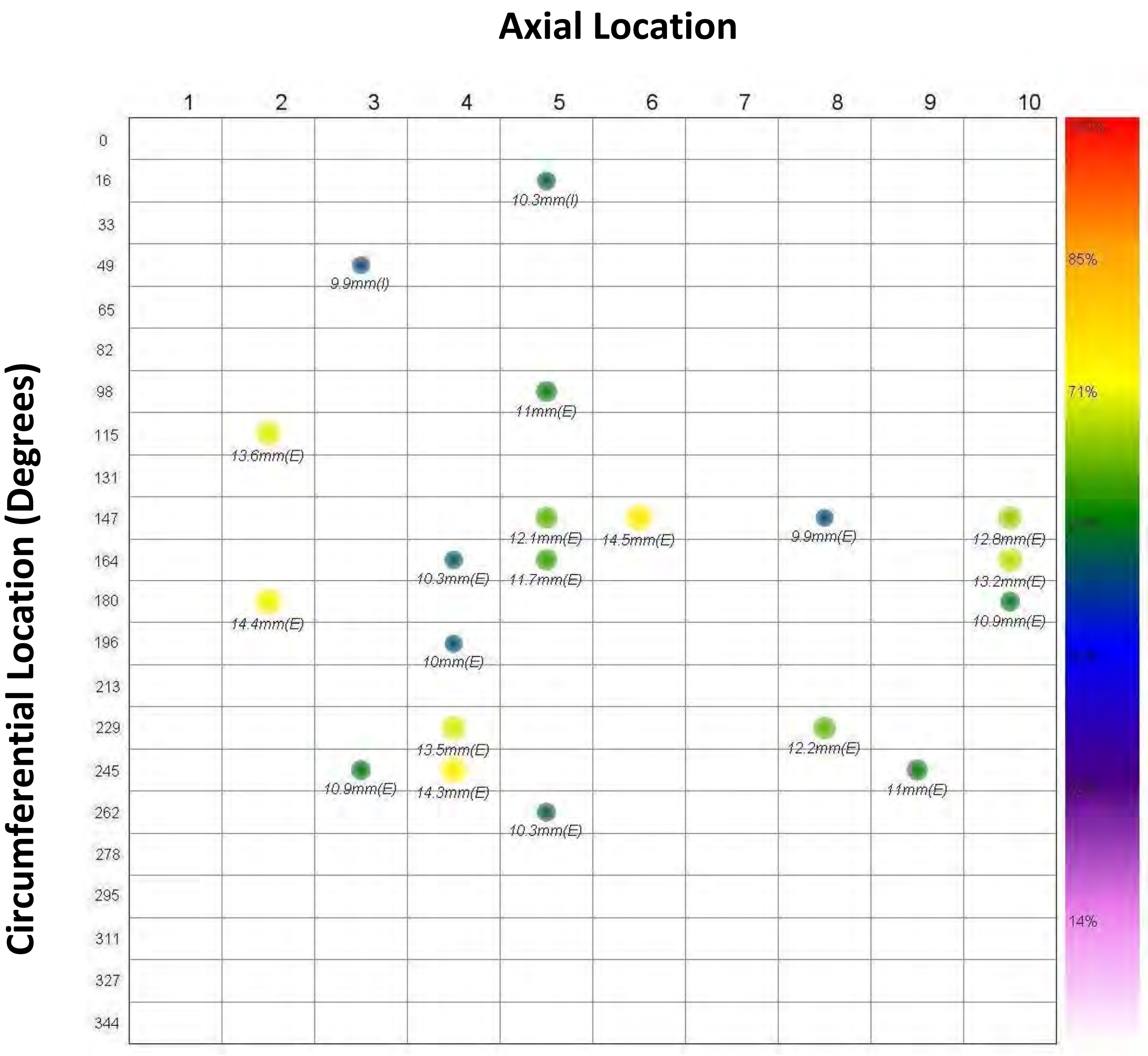
E = external
I = internal

(Courtesy of AESL)
Figure 5-19. Defect Plot for Pit 2 (20 Largest Defect Depths)



E = external
I = internal

Courtesy of AESL
Figure 5-20. Machined Defect Plot for Pit 2



E = external
I = internal

(courtesy of AESL)

Figure 5-21. Defect Plot for Pit L (20 Largest Defect Depths)

AESL also conducted a pipeline stress analysis assuming various loading regimes (soil overburden and traffic), membrane and bending stress, structural significance of the corrosion and fracture mechanics models to predict critical defect sizes for the risk of structural pipeline failure. The failure assessment diagrams (FADs) are provided in the AESL report and Table 5-14 summarizes the critical defect depth at the location of maximum stress for each of the excavated pits.

Table 5-14. Defect Depth to Cause Fracture

| **Pit** | **Load Case** | **Critical Defect Depth at Location of Maximum Stress (in.)** |
|---|---|---|
| F | Minor Road | 0.62 |
| 2 | Minor Road | 0.57 |
| L | Minor Road | 0.67 |

AESL's analysis of external defects indicated >65(23) through-wall defects and >63(23) critical defects. The 2/3 of the pipeline representative of Pits 2 and F likely has 15 through-wall defects, while the 1/3 of the pipeline representative of Pit L likely has >50 through-wall defects. With regard to critical defects, for the 2/3 of pipeline representative of Pit 2 and Pit F, there are potentially 13 critical defects ( ≥0.57-in.) and for the 1/3 of pipeline representative of Pit L, there are potentially >50 critical defects (≥0.67-in.) along the pipeline. Based on the estimated maximum stresses, defect distribution models, and assumed pipe material properties, AESL concluded that defects of sufficient depth to cause structural failure of the pipe may be present.

Because detailed pipeline material property data could not be provided to AESL due to the age of the pipeline system, there are uncertainties in the stress analysis and critical defect depth predictions. The identification of a historic American pipe standard for cast iron pipe would allow AESL to reduce the uncertainty in their assessment of original dimensions, material properties, and test pressures.

AESL also notes that there may be variations in the soil properties and hence corrosion drivers along the pipeline length, which may affect the validity of the statistical predictions.

Lastly, the fracture mechanics modeling conducted by AESL is based on a singular defect being present at a point of maximum stress to determine critical defects. Defects found in close proximity to each other are likely to give rise to higher stress concentration and therefore a further increase in the risk of structural failure.

**Comparison to Assessed Pipe Samples.** AESL took nondestructive measurements on the pipe and coating from 1-m wide sections around the pipe at Pits 2, F, and L, and also made soil measurements at ten accessible pit locations along the pipeline. AESL reported coating loss, wall thickness, and metal loss location and depth. AESL also used a systematic approach to extrapolate the data collected into a

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[23] These numbers are based on 2500-ft, which AESL was incorrectly given as the test pipe length instead of 2057-ft.

condition assessment for the entire pipe length. Specifically, AESL projected the number of potential through-wall defects and critical defects for the test pipe.

The machined defects in Pit 2 were distributed over a length of pipe greater than the 1 m that AESL scanned, so the verification had to be limited to those machined defects that AESL was able to scan in Pit 2. The AESL ECAT detection rate for the machined defects in Pit 2 was 100%, detecting six of six of the machined defects within their scan range. On average, AESL located anomalies within a small distance (2.6 inches) of the recorded defect location, but this apparent error may be attributed to differences between AESL's and EPA contractor's coordinate reference systems. ECAT's sizing accuracy is depicted in Figure 5-22 and Figure 5-23 in which the predicted and measured anomaly depths and lengths are presented. Ideally, the ECAT predicted values and the measured value should fall on the 45° line. The ±10 percent error is representative for MFL systems, and long skinny defects such as the ones in this pipe are difficult to accurately assess. The other 12 machined defects were not assessed by ECAT.

Under the demonstration program requirements, the ECAT MFL method used by AESL reported, in one case (Pit L; Pipe 30), a substantially larger number of corrosion pits greater than the size measured manually after grit blasting; and for Pit F, a similar number (5 vs. 3) of corrosion pits greater than 50% deep. For Pit L, AESL reported that for the 20 deepest pits, 18 of these were greater than 50% deep. The post assessment by EPA's contractor found one deep pit, at 68%, two pits near 50% (i.e., 46% and 47%), and many smaller pits. AESL may or may not remove the corrosion product within natural defects. While done for the first pipe assessed, AESL was asked not to do it for this pipe because this could possibly influence results for subsequent tests in the demonstration. Per AESL, removal or non-removal of corrosion does not affect AESL's calibration or sizing of defects, since the MFL inspection tools are calibrated prior to arrival on site and sizing models are based on a database of defects at AESL. The pipes in Pit 2 were not subjected to detailed assessment after the demonstration, so there is no data for direct comparison with AESL pit depth data.

The wall thickness data from ultrasonic devices were in good agreement from both AESL and EPA's contractor.

Fifteen internal defects were noted in the data. The concrete liner was in good condition and internal metal loss anomalies identified by AESL could not be found.

The project is focused on the innovative pipe wall integrity measuring devices, so EPA's contractor did not do an assessment comparable to AESL's assessment of soil characteristics or coating condition; nor did they perform modeling, statistical, or structural analyses to integrate and extrapolate indirect and direct data into a condition assessment for the full length of the test pipe.

AESL used a systematic and detailed approach to predict that there would be > 65 potential through-wall holes along a 2500-ft test pipe. While there are indications that this may be a significant overestimate, there are also mitigating factors that prevent a definite conclusion about the accuracy of the estimate. Indicators that an estimate of > 65 potential through-wall holes is high are: (a) no through-wall defects were found in the 144-ft (i.e., 7% of actual test pipe length) that was sandblasted and evaluated in detail; and (b) the leak detection phase of the study (Nestleroth et al., 2012), reported approximately 8 possible through-wall leaks/1000 ft, which, assuming a uniform leak density across the pipe, projects to 20 through-wall leaks over 2500-ft. However, there are insufficient data to eliminate the possibility that a substantial number of through-wall holes, or near- through-wall holes, do exist. For example: (a) only 12 of 171 (7%) of pipe lengths were measured in detail for wall loss and corrosion pits, so the actual number of through-wall holes in the remaining 93% of the test pipe is not known; (b) AESL collected metal loss data on only 0.5% of the test pipe, but they augmented their direct measurements with other relevant data, and then subjected the data to a logical and systematic analysis in order to generate their predictions of potential through-wall defects in the remainder of the pipe, and a comparable assessment was not within the EPA contractors' scope of work; (c) some through-wall holes may be present, but not leak due to plugging; and (d) AESL was given 2500-ft as the length of the test pipe, instead of 2057-ft, so this elevated their extrapolated number of potential through-wall holes; the EPA contractor's numbers were extrapolated to 2500-ft for the comparisons above.

AESL also used a systematic approach to determine the depth of a critical defect, and the number of critical defects. The project scope did not include a similar level of analysis by EPA's contractor, so no comparison of the number of critical defects was possible. AESL's analysis indicated that the first 1/3 of the pipe (i.e., nearest to Pit #1) had a substantially higher defect density than the remaining 2/3 of the pipe.

**Discussion.** The AESL ECAT MFL device successfully detected six of six machined defects. The measured defect depths ranged from 0.13-in. to 0.53-in. with the ECAT device reporting -47% to + 96% of the measured depths. The measured defect lengths ranged from 1-in. to 3.7-in. with the ECAT device reporting -45% to +210% of the measured lengths.

AESL's ECAT MFL device was operated successfully on three, 1-meter circumferential bands of pipe, representing about 0.5% of the full test pipe. AESL has a systematic, multi-step approach to collecting and analyzing direct and indirect pipe data that produces estimates of wall loss, number of through-wall defects, and size and number of critical defects that could potentially result in fracture failure. The ECAT device plays a critical role in the method by providing detailed data on the circumferential bands of pipe to the modeling and statistical processes that are used to analyze and extrapolate the data to the full length of pipe. AESL successfully demonstrated that they could implement their approach and produce the aforementioned estimates.

AESL's estimated numbers of through-wall defects and critical defects could not be rigorously evaluated for the reasons cited in the previous section.

Other factors in addition to those cited in the previous section may also have influenced AESL's findings. One excavated pipe location used by AESL was near a large leak, which may have contributed to higher corrosion rates that may have biased the extrapolations towards larger defects. Some procedural differences occurred in the selection of the assessment points, and assessment of detect, which could have influenced the results. For example, AESL would normally select the assessment points, but the selection was influenced by the test program requirements. Additionally, the sizing software used by AESL is based on calibration scans of flat-bottomed corrosion defects from different pipes of different wall thicknesses and potentially different magnetic properties. As such, this demonstration provides a unique opportunity for AESL to improve their sizing algorithms based on the more complex geometry of natural defects found in the test pipe.

AESL's approach has the advantages of not requiring entry into the pipe or disrupting flow. Also, only selected locations along the pipe require excavation. The ECAT is equipped with GPS and blue tooth technology that is used to enable data transfer in real-time.

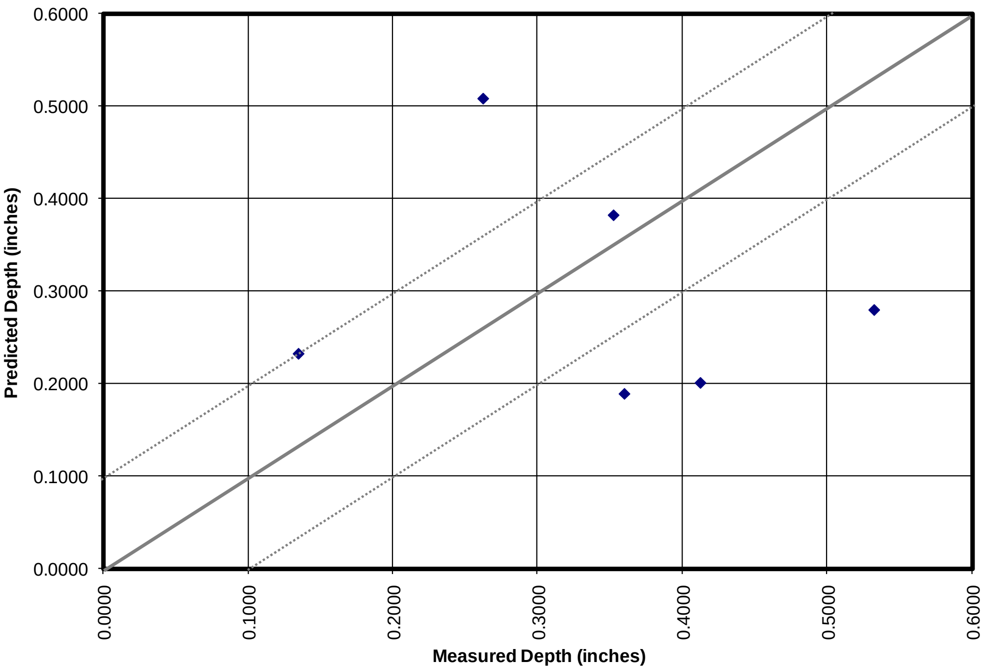


Figure 5-22. Measured Depth vs. Predicted Depth for the AESL ECAT for Machined Defects in Pit 2

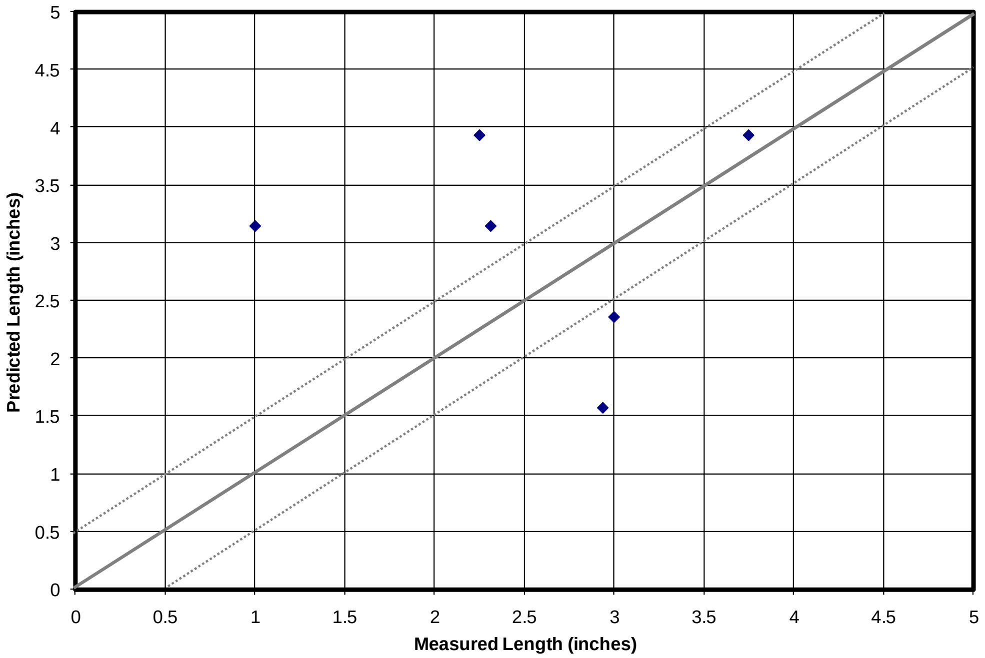


Figure 5-23. Measured Length vs. Predicted Length for the AESL ECAT for Machined Defects in Pit 2

### 5.3.2 RSG HSK and CAP

**Summary of Results.** In general, the RSG results indicate that there is notable metal loss in the sections of pipe scanned during the demonstration. RSG did not find a common wall thinning trend for the entire pipeline length and indicated that the trends appear to be section specific. The minimum wall thickness recorded was in Pit C at 0.627 in. Detailed plots for each excavation location are provided in Figure 5-24 through Figure 5-32 with a summary of the results provided in Table 5-15.

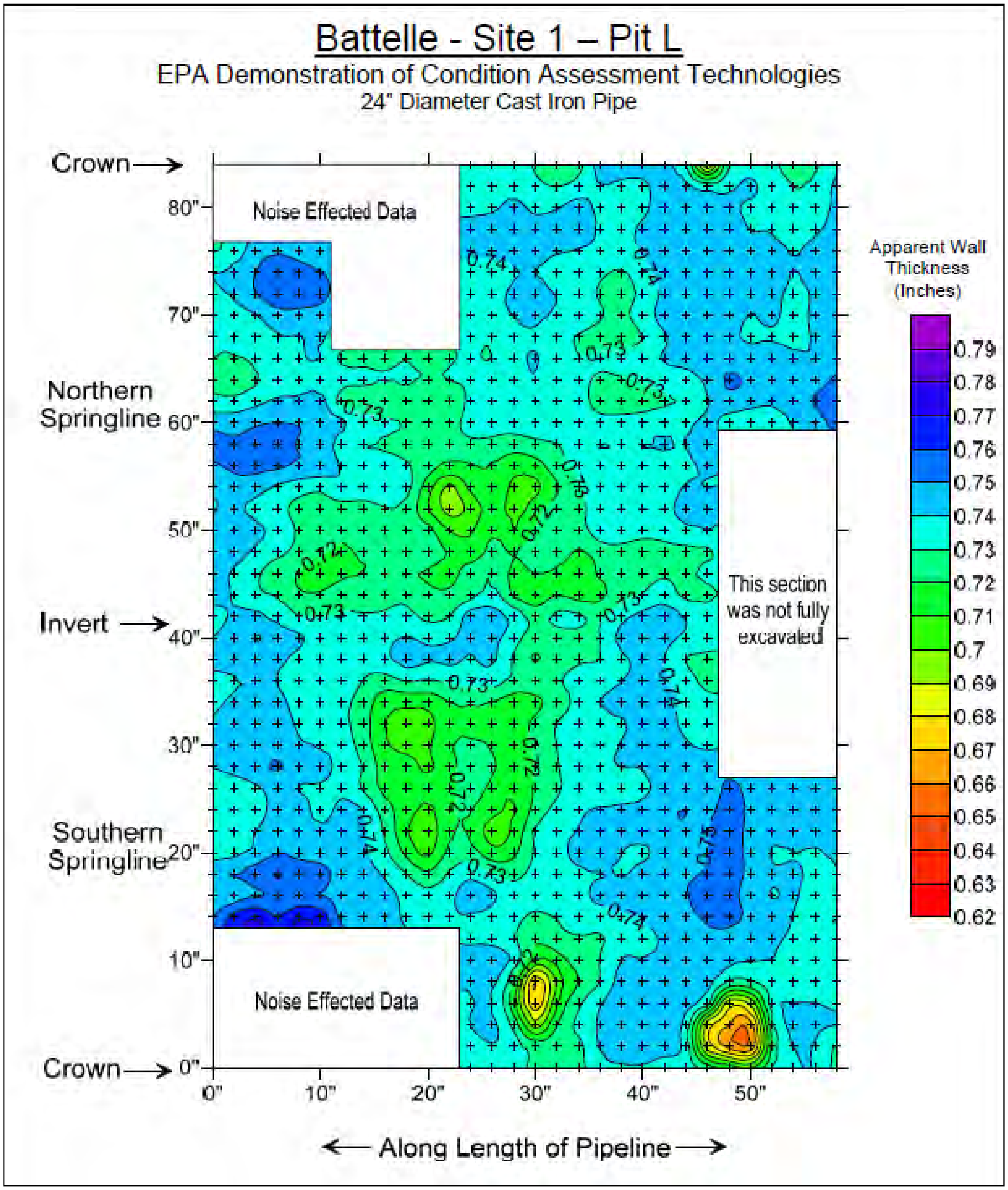
**Comparison to Assessed Pipe Samples.** The method provided local wall thickness values at nominally 250 ft intervals on the top of the pipe and full pipe circumference measurements in three locations. These readings did not discover significant metal loss that would indicate that the condition of the pipe was poor. RSG only provided relative wall thinning data averaged over the sensor area. The sensors are on a 1-in. spacing in both the axial and circumferential direction for CAP and a 2-in. spacing in both the axial and circumferential direction for HSK. A single reading is provided for each sensor, averaging over the sensor aperture. CAP and HSK did not offer the sensitivity needed for direct comparison with the machined defect data. Only general comments can be made regarding possible increased wall thinning in the location of the machined defects. The HSK scan of Pit F, which contained fairly large machined defects (35% to 59% wall loss over a 6-in. length), did indicate areas of reduced wall thickness over a 6-in. length near the crown of the pipe; however, since the results were averaged there is not sufficient granularity to directly compare the scans with the actual depths of the machined defects in Pit F (RSG reported minimum wall thickness of 0.678-in. , but the measured minimum of the machined defects is approximately 0.3-in.).

**Discussion.** The RSG HSK and CAP results did not detect any large corrosion areas, which compared well with the general condition of the pipe. Due to the manner in which the HSK and CAP technologies report data (e.g., wall thinning data averaged over the sensor aperture area), it is not possible to do a one-for-one comparison with the measurements recorded for the machined defects in Pits 2 and F.

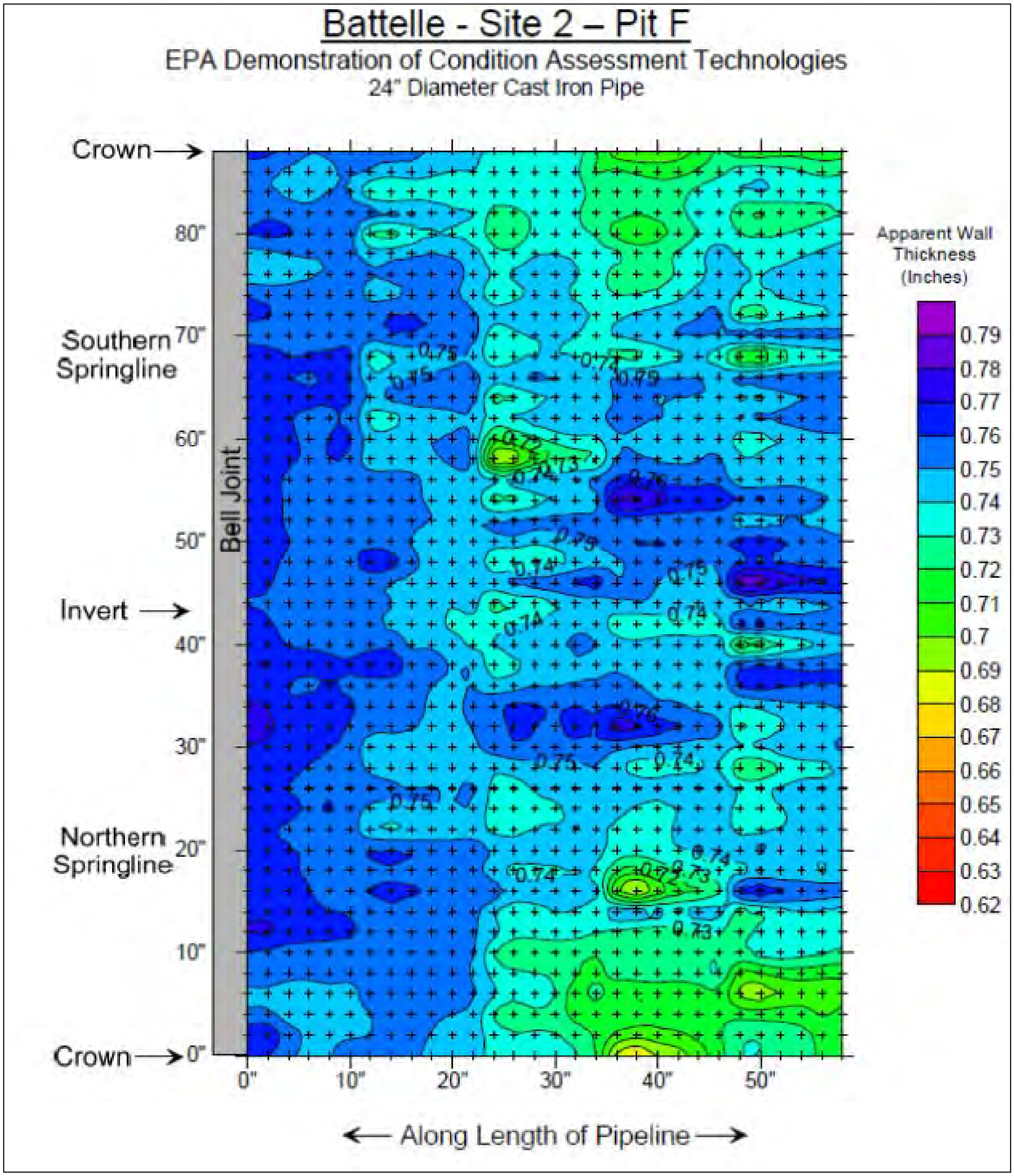
Table 5-15. Summarized RSG Condition Assessment Results for Pit A to F, Pit 2, and Pit L

| Location [ft] | Type of Scan | Minimum Wall Thickness [in.] | Average Wall Thickness [in.] | Summarized Condition Assessment Results |
|---|---|---|---|---|
| 250<br>(Pit A) | CAP | 0.662 | 0.737 | ∗ Moderate corrosion near the pipe crown (Fig. 5-26) |
| 338<br>(Pit L) | HSK | 0.654 | 0.735 | ∗ Higher degree of wall thinning near the pipe crown<br>∗ Moderate degree of wall thinning at the pipe sides<br>∗ One section could not be scanned due to access restrictions; BEM data could not be analyzed for two sections due to noise interference (Fig. 5-24) |
| 510<br>(Pit B) | CAP | 0.680 | 0.719 | ∗ Moderate corrosion near the pipe crown (Fig 5-27) |
| 809<br>(Pit C) | CAP | 0.627 | 0.703 | ∗ Most severe corrosion near the pipe crown (Fig. 5-28) |
| 1,080<br>(Pit 2) | HSK | 0.688 | 0.735 | ∗ Moderate to severe corrosion on the southern side of the pipe<br>∗ Moderate corrosion at the bottom of the pipe (Fig. 5-30) |
| 1,173<br>(Pit D) | CAP | 0.666 | 0.689 | ∗ Moderate corrosion near the pipe crown (Fig. 5-29) |
| 1,439<br>(Pit E) | CAP | 0.704 | 0.709 | ∗ Negligible wall thickness variation (Fig. 5-32) |

| Location [ft] | Type of Scan | Minimum Wall Thickness [in.] | Average Wall Thickness [in.] | Summarized Condition Assessment Results |
|---|---|---|---|---|
| 1,750<br>(Pit F) | HSK | 0.678 to 0.711 | 0.745 to 0.748 | ∗ Higher degree of wall thinning near pipe crown<br>∗ Moderate degree of wall thinning at the pipe sides; more prevalent on northern side<br>∗ Thinning in isolated areas; therefore likely due to pitting clusters or graphitization<br>∗ (Fig 5-25 and 5-31; two different lengths of pipe in the same pit, separated by b/s joint). |

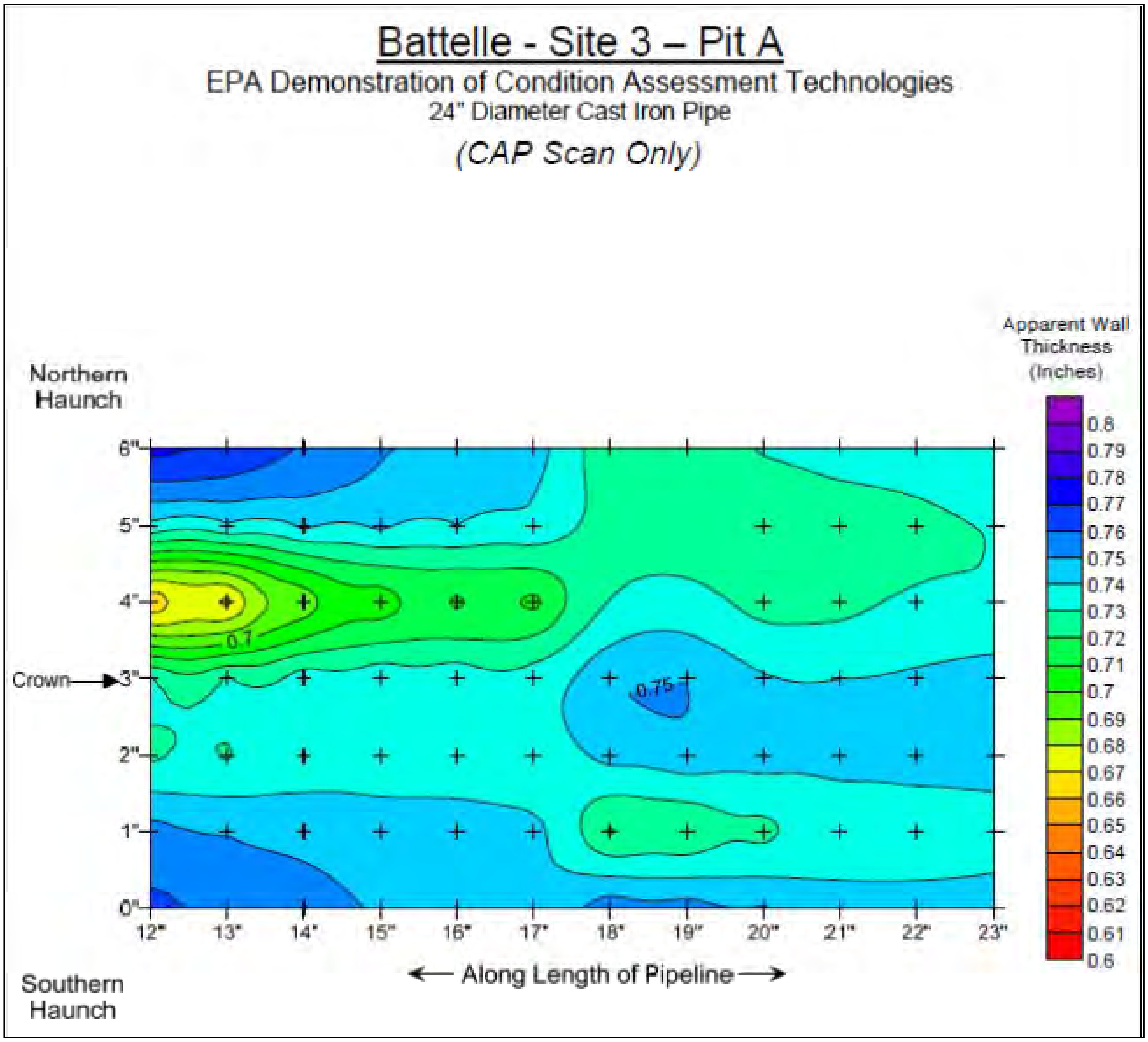


(Courtesy of RSG)
Figure 5-24.  HSK Data Plot – Pit L



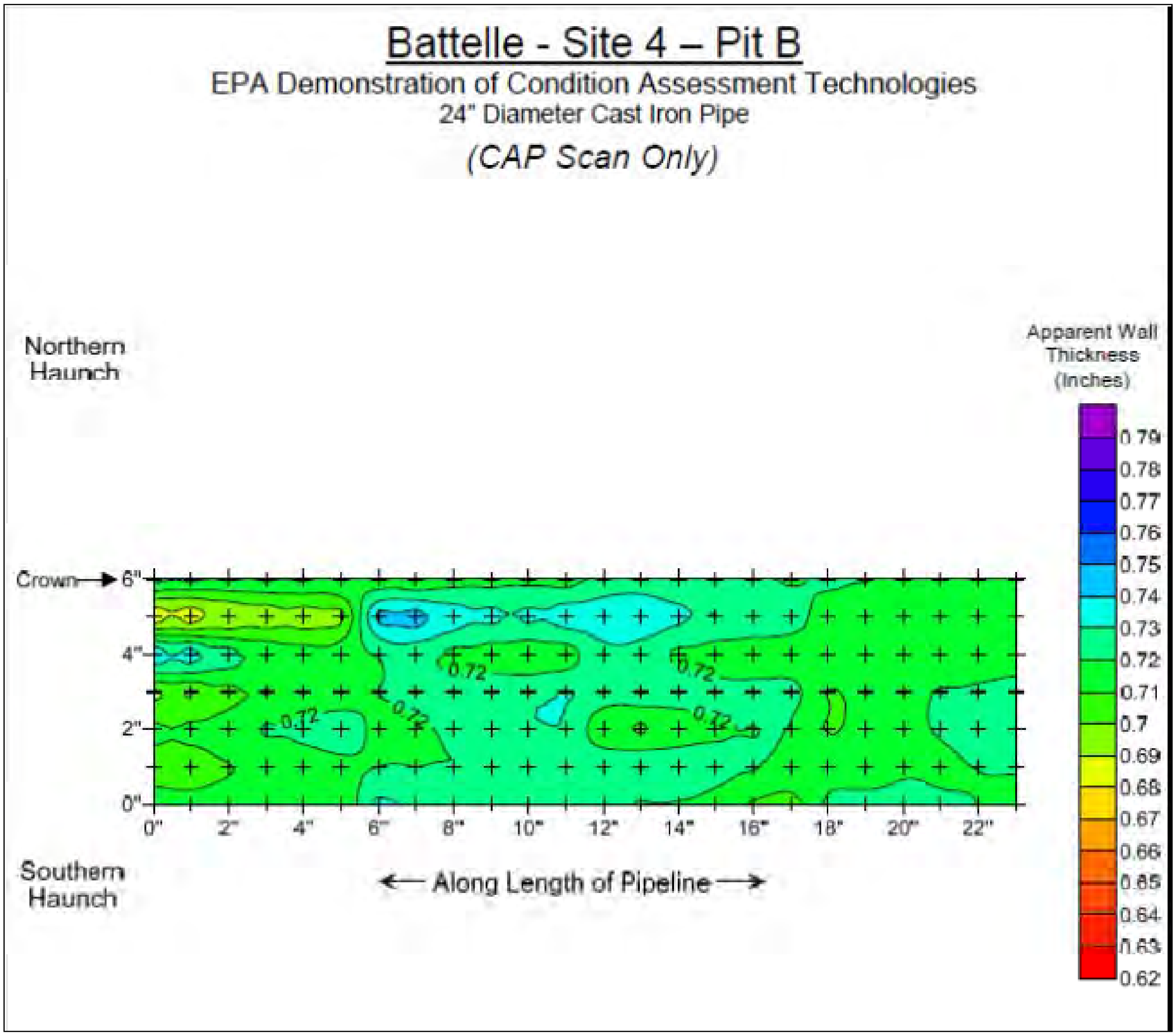
(Courtesy of RSG)

Figure 5-25. HSK Data Plot – Pit F



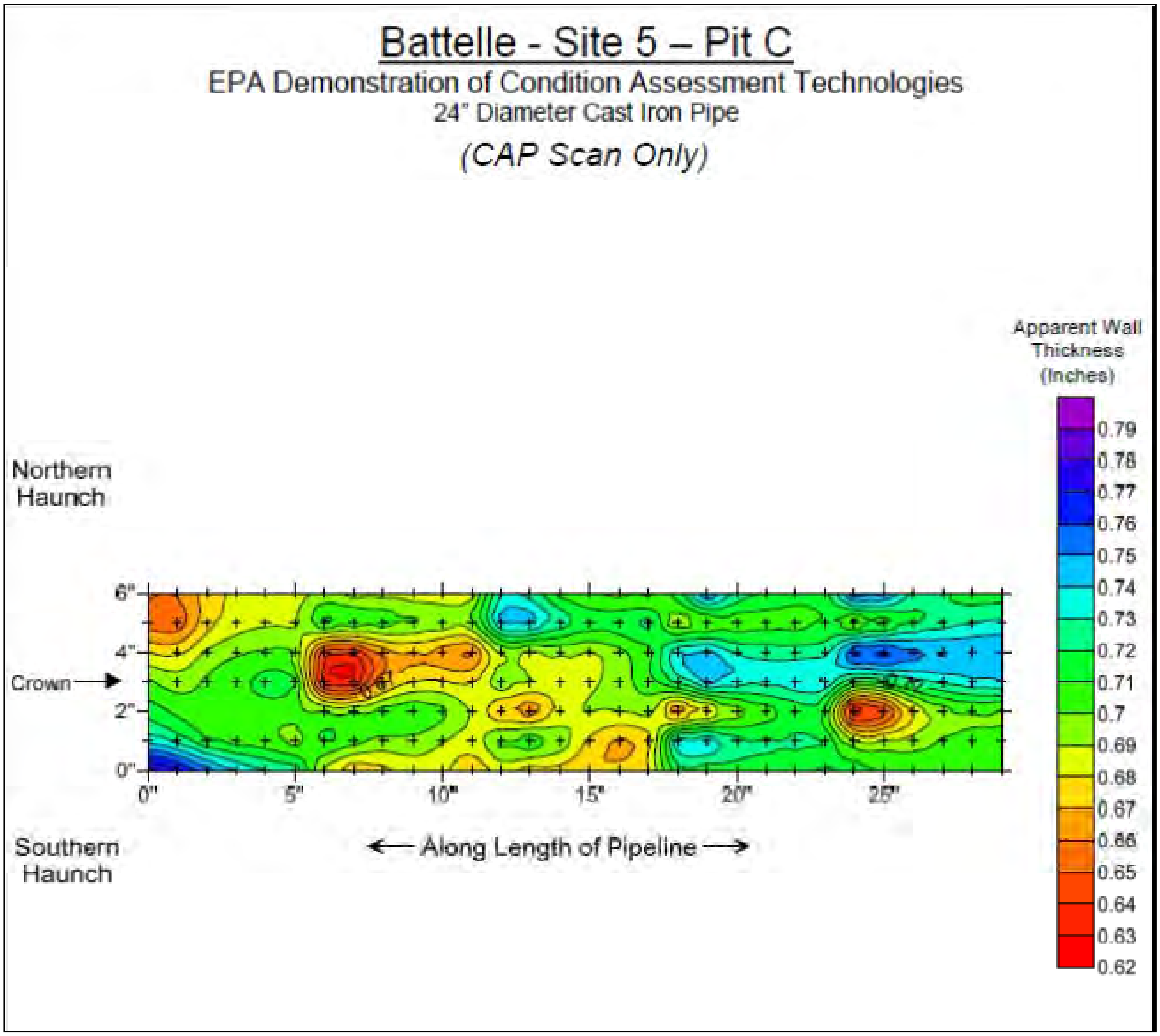
(Courtesy of RSG)

Figure 5-26. CAP Data Plot – Pit A



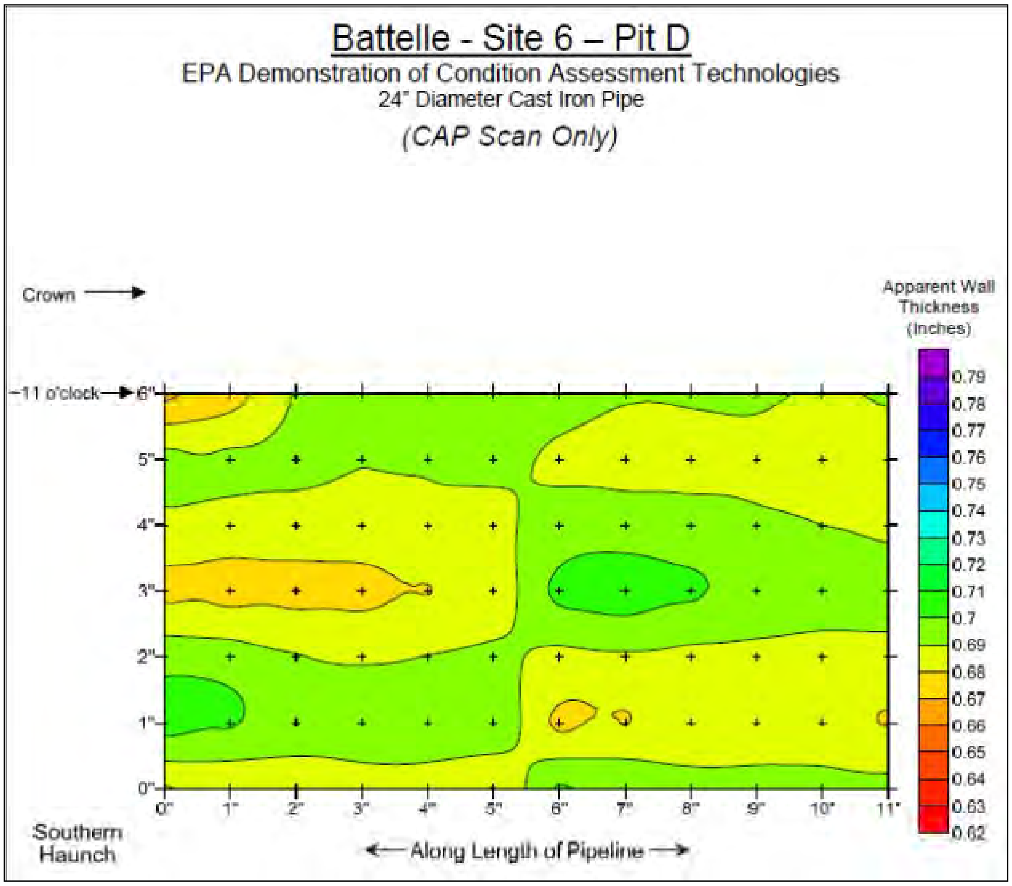
(Courtesy of RSG)

Figure 5-27. CAP Data Plot – Pit B



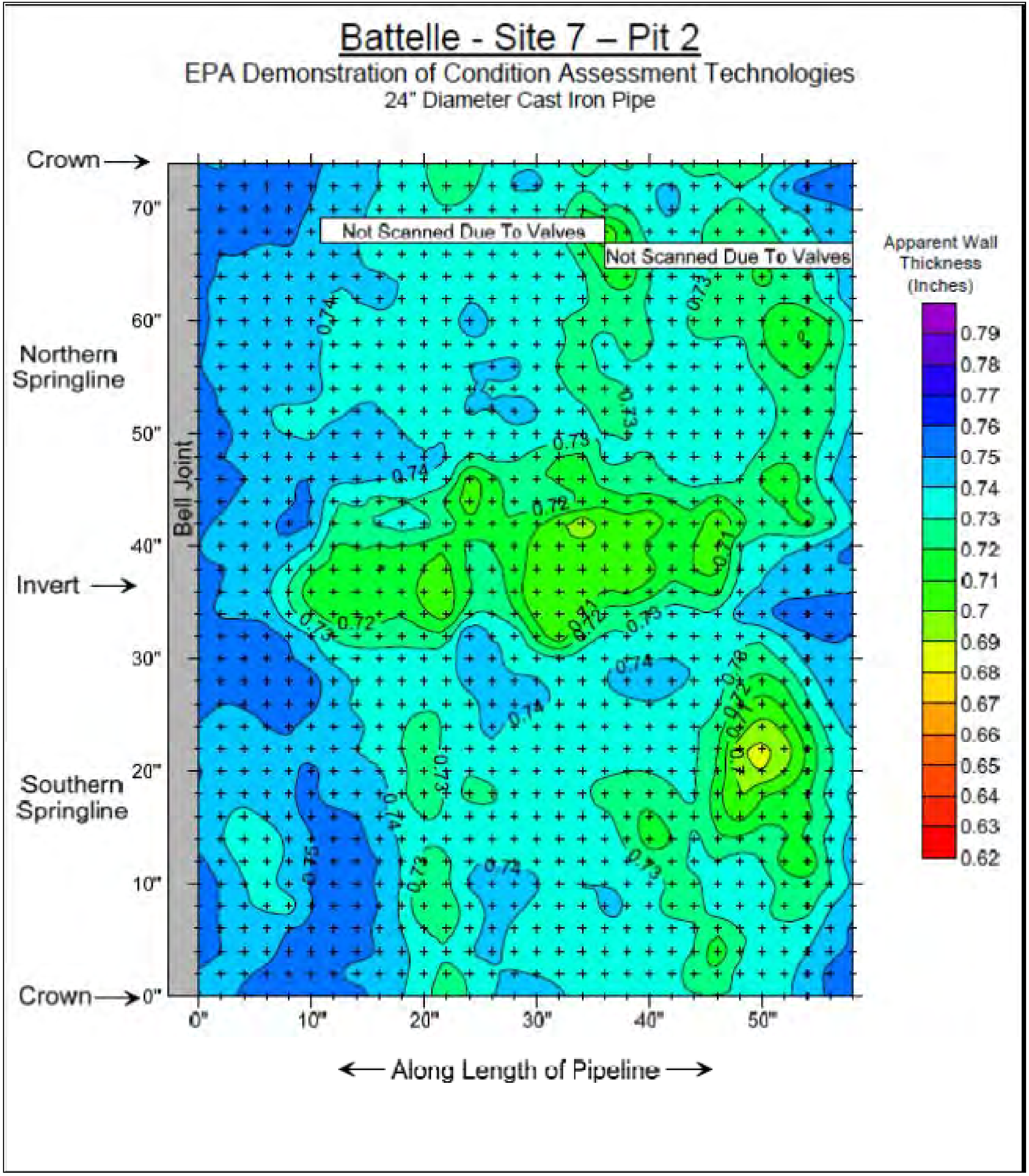
(Courtesy of RSG)

**Figure 5-28. CAP Data Plot – Pit C**



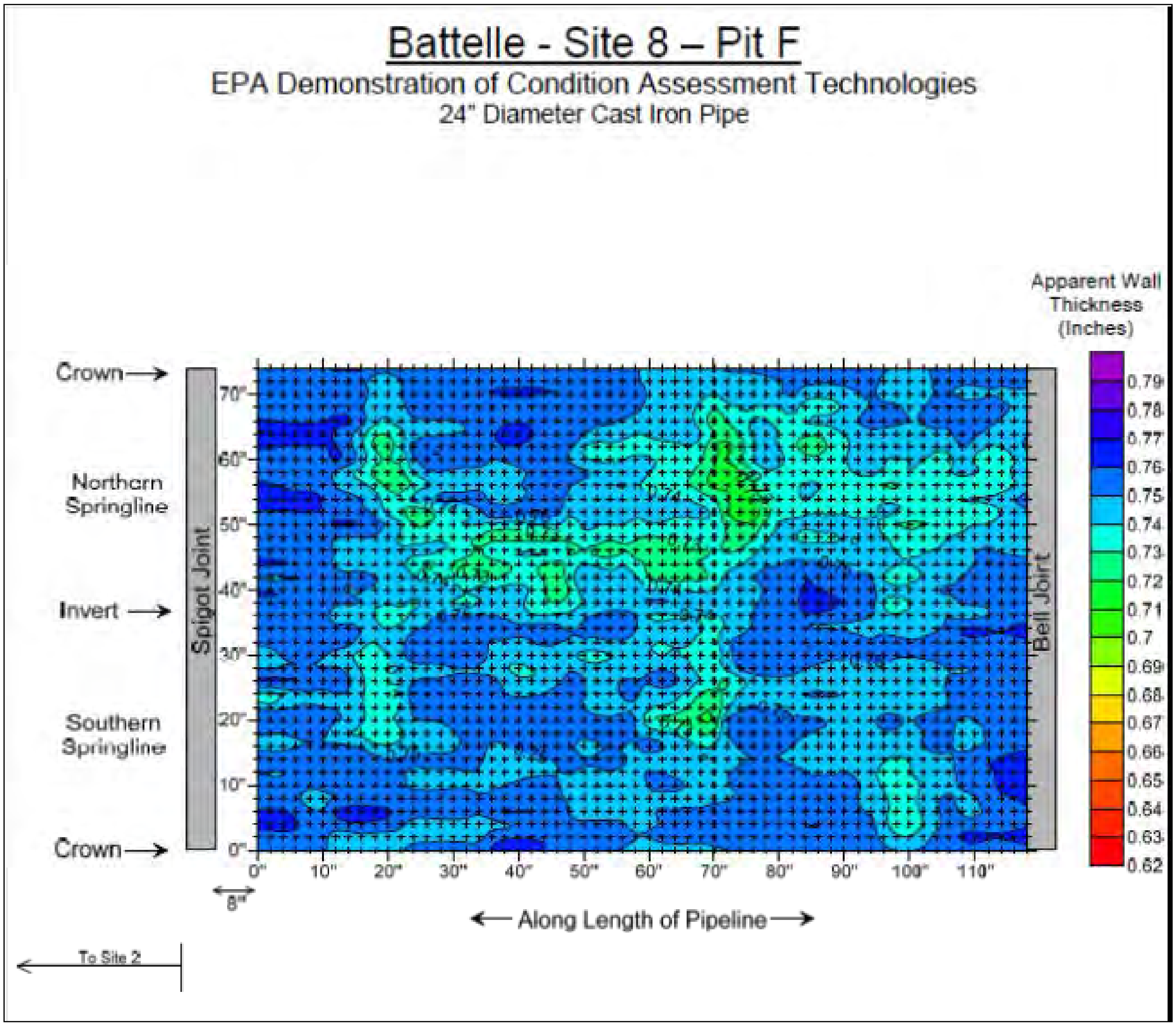
(Courtesy of RSG)

Figure 5-29.  CAP Data Plot – Pit D



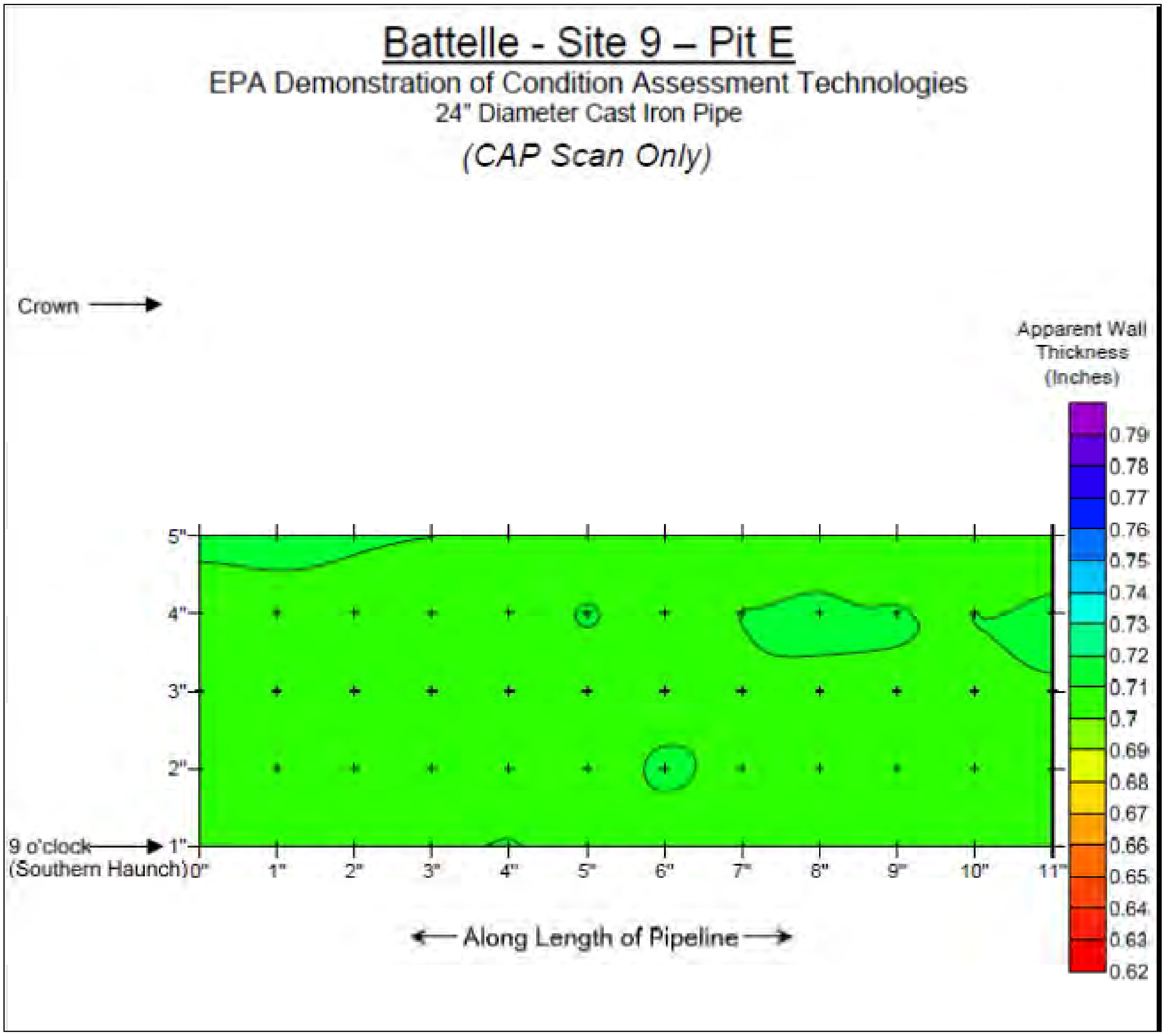
(Courtesy of RSG)

Figure 5-30. HSK Data Plot – Pit 2



(Courtesy of RSG)

Figure 5-31. HSK Data Plot – Pit F



(Courtesy of RSG)

**Figure 5-32. CAP Data Plot – Pit E**

## 5.4 Cost of Technologies

The cost of an inspection has two main components: (1) the cost of the service provided by the inspection vendor; and (2) the cost for the water company to prepare the line and conduct the inspection, which is often more difficult to quantify. The costs are described below for the acoustic pipe wall surveys, internal inspection technologies, and external inspection technologies for a specific case and time (i.e., 2009).

**5.4.1 Acoustic Pipe Wall Survey Costs**. The cost to conduct an average wall thickness survey is dependent on a number of variables including the length and diameter of pipe to be inspected, pipe accessibility, and types of services requested (some vendors offer volume discounts for leak detection and condition assessment services). Costs usually include mobilization/demobilization, inspection (per ft or mile), tap installation (if required), travel, and data analysis and reporting.

To supplement the cost information gathered for the demonstration, EPA's contractor also requested that the vendors provide a cost estimate for inspecting 10,000 ft of 24-in. cast iron pipe along the same route as the demonstration in Louisville, KY. They were asked to include in their cost estimates:

- The cost of conducting a leak survey alone
- The cost of conducting a pipe wall thickness assessment alone
- The cost of conducting both (leak and pipe wall thickness survey) at the same time.

Each vendor was given drawings of the 30-in. diameter pipeline that replaced the test pipe used for the demonstration. The vendors were instructed that the pipeline for the cost estimate would follow the route of the 30-in. line, but to assume that the line is 24-in. diameter and 10,000 ft in length.

To the extent possible, the vendors were asked to supply with their cost estimates:

- Mobilization/demobilization costs
- Inspection costs (including data analysis and reporting)
- Factors that can affect pricing, such as diameter, length, risers, valves, bends, tees, insertions, etc. and how these factors might impact the cost
- Costs for line modifications to perform the inspection are typically the responsibility of the utility and are provided in Section 5.4.2.

Since some details regarding the pipeline and its location were not well defined, the vendors were informed that a range of costs was acceptable.

**PPIC Sahara®.** For a 24-in. diameter, 10,000 ft long cast iron pipe, the cost estimates for a Sahara® leak and/or pipe wall thickness inspection are provided in Table 5-16. Costs were not broken out by individual activity (e.g., data acquisition, data analysis, reporting, etc.). Charges for mobilization/ demobilization are $4,000, while data analysis and reporting are included in the price of the survey.

As reported by PPIC, each site inspection has different factors that may result in modification costs for either the client or inspection vendor. Pipeline and operational parameters, such as pipeline length, access preparation, features, flow condition, etc. can affect pricing. Proper pre-inspection preparation (drawings, access preparation, flow rate control, etc.) by the client can significantly increase productivity, while reducing the overall cost of the inspection. Inspecting longer lengths of pipe at the same time can benefit from long-term program pricing discounts.

**Table 5-16. PPIC Sahara® Cost Estimates for Inspection of a 24-in. Diameter, 10,000 ft Long Cast Iron Pipeline**

| Type of Survey | Cost Estimate |
|---|---|
| Leak and gas pocket survey (includes data acquisition, data | $22,000 |

| | |
|---|---|
| analysis, and final report) | |
| Pipe wall thickness survey (includes data acquisition, data analysis, and final report) | $33,000 |
| Leak and gas pocket AND pipe wall thickness survey (includes data acquisition, data analysis, and final report) | $44,000 |

**Pure SmartBall$^{TM}$.** Pure provided a range of costs to conduct three types of surveys: (1) a leak and gas pocket survey, (2) a pipe wall thickness survey, and (3) both leak and pipe wall thickness surveys on one mobilization. Line modifications would be required of the client to install two 4-in. taps, one at the beginning and one at the end of the survey length. Pipeline flow would also need to be maintained between 1.5 and 2 ft/s and pipeline pressure above 10 psi. Pure stated that it was possible to conduct a leak survey at lower pipeline pressures, but the accuracy of the results could sometimes be compromised. Pure also stated that these prices were to be used as a guideline and not as fact for inspection projects of this size.

For a 24-in. diameter, 10,000 ft long cast iron pipe, the cost estimates for a SmartBall$^{TM}$ inspection are provided in Table 5-17. Costs were not broken out by individual activity (e.g., mobilization, data acquisition, reporting, etc.). Charges for mobilization, demobilization, data acquisition, data analysis, and final report run between $25,000 and $40,000 per inspection depending on which technology is used.

This type of survey would require two days on site, one to do a site review with the client and an actual day of work with the tool in the pipeline. Pure can produce an on-site interim report and the final report within two weeks of completing the survey. The interim report generated just after the survey, while the field crew is still on site would cost an additional $3,000 to $5,000.

**Table 5-17. Pure SmartBall$^{TM}$ Cost Estimates for Inspection of a 24-in. Diameter, 10,000 ft Long Cast Iron Pipeline**

| Type of Survey | Cost Estimate |
|---|---|
| Leak and gas pocket survey (includes mob/demob, data acquisition, data analysis, technology charges, and final report) | $40,000 to $50,000 |
| Pipe wall thickness survey (includes mob/demob, data acquisition, data analysis, technology charges, and final report) | $55,000 to $65,000 |
| Leak and gas pocket AND pipe wall thickness survey (includes mob/demob, data acquisition, data analysis, technology charges, and final report) | $80,000 to $90,000 |

**Echologics LeakfinderRT.** Echologics provided a fairly detailed cost proposal describing the work to be done for executing leak and condition assessment surveys for a 24-in. diameter, 10,000 ft long cast iron pipeline. Preparation work would be required by the client before the arrival of Echologics field technicians and includes:

- Assess traffic management requirements and prepare a traffic management plan.
- Identify confined space entry locations and provide a confined space entry plan and necessary equipment.

- Identify all fittings to be used for the inspection and mark with blue spray paint or the equivalent.
- All fittings should be in working order with no leaking seals or joints when under pressure. Any leaking fittings must be repaired before the inspection. Failure to do so prevents accurate data from being acquired in this location.
- Any valves installed on the pipe to be surveyed should be operated, if possible, to make sure they are fully open. Any boundary/closed valves should be acoustic sounded to make sure the valve is not passing water.
- Valve boxes, chambers, and vaults are to be cleared of debris prior to the inspection. Failure to meet this requirement will prompt the need for an on-call VAC truck for the duration of the project.
- Provide detailed maps, plans, and as-built drawings, if possible, showing all pipe fittings and any other essential distribution information to establish a data acquisition plan.
- Provide all repairs and rehabilitation history, if possible, on the section of pipe to be surveyed.
- Air must not be present in the main and all air relief valves must be in good working order and inspected prior to the start of the survey. If air is present, flushing must be undertaken to eliminate any trapped air.
- Pipe pressure must be maintained at a minimum working pressure of 25 psi with a maximum pressure of 150 psi. Anything outside of these limits will require special consideration.

Echologics also requires the provision of an experienced water operator with a fully equipped truck for the duration of the project. These requirements are necessary to accomplish the project within the proposed timeline and budget.

For the condition assessment survey, Echologics requires access to the pipe every 300 to 400 ft through the use of vacuum excavated potholes. The potholes should measure 6 to 8-in. in diameter and provide access to the top of the pipe. Data acquisition will be performed using magnetic surface mounted sensors attached to available fittings or the pipe surface. Fire hydrants will need to be flushed to take the water temperature at each measurement site. Pipeline installation date and site-specific pipe manufacturer data must be provided prior to field work.

Echologics provided cost estimates for mobilization, data acquisition, data analysis, and final reporting. Mobilization includes all of the preparation work required by Echologics field technicians along with travel and shipping expenses. Data acquisition will take approximately three to five days with two field technicians. Generally, it is possible to cover between 2,500 ft and 5,000 ft of pipe per day. If any leaks are discovered during the data acquisition process, it will be the decision of the client as to whether or not a detailed investigation will be performed to pinpoint the location of the leak. Data analysis includes the time required to analyze the acoustic recordings upon completion of data acquisition using proprietary processes. The analysis time will depend on the pipe size and total length of pipe surveyed. The final report will summarize all of the results and include background, methodology, sources of error, data interpretation methods, analysis, results, and final recommendations. A draft report will be submitted to the client prior to its finalization. For a 24-in. diameter, 10,000 ft long cast iron pipe, the cost estimates for a LeakfinderRT inspection are provided in Table 5-18.

For a condition assessment and leak detection survey, Echologics estimated a total of four to five days on site and an additional 22 hours of data analysis and final report preparation.

**Table 5-18. Echologics LeakfinderRT Cost Estimates for Inspection of a 24-in. Diameter, 10,000 ft Long Cast Iron Pipeline**

| Type of Survey | Cost Estimate |
|---|---|
| Leak detection survey | |
| Mobilization | $3,000 |
| Data Acquisition | $12,500 |
| Data Analysis | $2,500 |
| Reporting | $2,310 |
| **Total** | **$20,310** |
| Condition assessment and leak detection | |
| Mobilization | $3,500 |
| Data Acquisition | $15,000 |
| Data Analysis | $5,000 |
| Reporting | $3,630 |
| **Total** | **$27,130** |

### 5.4.2 Internal Inspection Technology Costs

**PPIC PipeDiver™.** Since the PipeDiver™ system is currently in the development stage, commercial pricing was not available. The cost elements would be expected to include: mobilization of the inspection crew; inspection and data acquisition on the 10,000 ft of 24-in. pipe, which is expected to take one day to inspect; use of a crane or backhoe and operator for tube placement (included in site preparation cost below); and data analysis and reporting, which would take up to eight weeks after the inspection.

**PPIC Sahara® Video.** Since the PPIC Sahara® Video was in development at the time the demonstration report was submitted, PPIC and then Pure declined to give a cost estimate. The cost elements would be expected to include: mobilization of the inspection crew; inspection and data acquisition on the 10,000 ft of 24-in. pipe; and data analysis and reporting.

**Russell NDE Systems Inc. See Snake®.** Russell NDE Systems Inc. provided a detailed cost proposal describing the work to be done for executing the condition assessment survey for a 24-in. diameter, 10,000 ft long cast iron pipeline using the free swimming operation. The free swimming operation was recommended over the tethered operation, which is typically applicable for lengths less than 3,000 ft with no more than three elbows. Site preparation work that would be required by the client before the arrival of the NDE Systems Inc. team includes:

- Assess traffic management requirements and prepare a traffic management plan.
- Isolation of the line to be inspected and preparation of two access pits with trench boxes for tool launching and receiving.
- Removal of 10 ft of pipe in each access pit for tool launching and receiving.
- Cleaning of the line before inspection.

Russell NDE Systems Inc. also requires an experienced water operator to operate valves and control water flow during inspection and an equipment operator to assist with launching and removal of the tool form the access pits. These requirements are necessary to accomplish the project within the proposed timeline and budget.

Russell NDE Systems Inc. provided cost estimates for mobilization/demobilization, bore proofing (i.e., ensuring the bore diameter is sufficient along the length of the pipe), launch and receive barrel rental, inspection, and data analysis and reporting. Mobilization includes travel to and from the site and shipping expenses. Inspection and data acquisition is estimated to take two days, covering about 5,000 ft of pipe per day. For a 24-in. diameter, 10,000 ft long cast iron pipe, the cost estimates for a See Snake inspection are provided in Table 5-19.

**Table 5-19. Russell NDE Systems Inc. See Snake® Cost Estimates for Inspection of a 24-in. Diameter, 10,000 ft Long Cast Iron Pipeline**

| Type of Survey | Cost Estimate |
|---|---|
| Free swimming operation (barrel rental included) | |
| Mobilization/Demobilization | $20,000 |
| Bore Proofing | $10,000 |
| Launch & Receive Barrel Rental | $40,000 |
| Inspection Fee | $60,000 |
| Analysis and Reporting Fee | $60,000 |
| **Total** | **$190,000** |
| Free swimming operation (barrel rental not included) | |
| Mobilization/Demobilization | $20,000 |
| Bore Proofing | $10,000 |
| Inspection Fee | $60,000 |
| Analysis and Reporting Fee | $60,000 |
| **Total** | **$150,000** |

### 5.4.3 External Inspection Technology Costs

**AESL ECAT**. AESL provided a lump sum cost proposal for executing the condition assessment survey for a 24-in. diameter, 10,000 ft long cast iron pipeline. The costs provided by AESL include mobilization and demobilization from Northumberland, UK and have been broken down into inspection only and inspection with condition assessment. Site preparation work that would be required prior to the inspection would include excavations with trench boxes roughly every 1,200 ft, which would require roughly nine excavations. The costs for inspecting a 24-in. diameter, 10,000 ft long cast iron pipe by AESL are provided in Table 5-20.

**Table 5-20. AESL ECAT Cost Estimates for Inspection of a 24-in. Diameter, 10,000 ft Long Cast Iron Pipeline**

| Type of Survey | Cost Estimate |
|---|---|
| Inspection Only | $27,414 |
| Inspection with Condition Assessment | $35,963 |

**RSG HSK.** RSG provided a lump sum cost proposal for executing the condition assessment survey with HSK for a 24-in. diameter, 10,000 ft long cast iron pipe. Costs associated with the use of CAP were not included. The proposed survey included 13 locations evenly distributed along the pipe length (except where the pipe ran below a railroad track where additional scans were proposed on both sides of the track). The scanning would cover the full pipe circumference, with 100% pipe surface coverage, for a pipe length of 5 ft at each location. It was estimated that between four to five sites could be scanned per day and 3 days of pipe scanning were accounted for in the cost estimate. Real-time results would be made available on site following the completion of each scan and preliminary processed plots within one week. Post-survey processing, plotting, analysis, and reporting would be submitted within 4 weeks of field work completion.

The costs for inspecting a 24-in. diameter, 10,000 ft long cast iron pipe by RSG HSK are provided in Table 5-21. The cost elements would include: mobilization to the site; establishment at the site; 3 days of field work; provision of scanning equipment; provision of results on site; and demobilization from site. The water utility would be responsible for all excavation work, reinstatement of soils at each location, surface restoration, traffic control and safety of excavations, permitting, and other site preparation work.

**Table 5-21. Rock Solid HSK Cost Estimates for Inspection of a 24-in Diameter, 10,000 ft Long Cast Iron Pipeline**

| Type of Survey | Cost Estimate |
|---|---|
| External Inspection at 13 Locations | $29,460 |

**5.4.4 Site Preparation Costs.** The inspection costs presented above do not include the cost for the water utilities to prepare the pipe and provide traffic control and other logistical support.

The site preparation costs for line modification and field support are highly site-specific and for this reason the estimates provided are order of magnitude estimates based upon typical construction costs (RSMeans, 2011). The actual site preparation costs for a given site will depend upon regional costs for construction labor, along with factors such as the access requirements, availability and condition of existing hydrants/valves, length of deployment, days on site, and more.

It is estimated that the site preparation costs to conduct a wall thickness survey of 10,000 ft of 24-in. diameter cast iron pipe may range in magnitude from $0.48/ft to $0.69/ft (including traffic control, pit/pothole excavation, tapping, backfill, and restoration). It is estimated that site preparation costs for an internal inspection of 10,000 ft of 24-in. diameter cast iron pipe may be approximately $0.58/ft (including traffic control, pit excavation, tapping, backfill, and restoration). It is estimated that site preparation costs for an external inspection of 10,000 ft of 24-in. diameter cast iron pipe may range in magnitude from $0.94/ft to $1.63/ft (with 9 to 13 excavated locations, respectively).

**Acoustic Pipe Wall Assessment Technologies.** During a Sahara® WTT inspection, a 1-in. diameter hydrophone is inserted into a live main through a 2-in. tap. The maximum length of inspection is 6,000 ft based on the umbilical cable length. For purposes of this cost estimate, it is assumed that two required access points must be installed for a 10,000 ft pipe inspection (e.g., no existing taps are used). Another 24 potholes to position a sensor on top of the pipe (i.e., one every 400 ft) would also be required. Table 5-22 estimates the site preparation costs based upon the required excavations and the installation of two 2-in. taps for a Sahara® WTT inspection.

During an inspection, SmartBall™ can be inserted into the pipeline through existing hydrants or any valve configuration with greater than 4-in. diameter clearance. SmartBall™ is then retrieved through another 4-in. or greater valve. For purposes of this cost estimate, it is assumed that the two required access points must be installed for a 10,000 ft pipe inspection (e.g., no existing hydrants or valves are used). Another nine smaller pits to position a sensor on top of the pipe (i.e., one every 1,000 ft) would also be required. Table 5-23 estimates the site preparation costs based upon the required excavations and installation of two 4-in. taps for a SmartBall™ inspection (with pits located at 0 ft and 10,000 ft).

Echologics mounts accelerometers directly on the pipe surface (using magnetic surface mounted sensors attached to available fittings or the pipe surface). For purposes of this cost estimate, it is assumed that 26 pothole excavations (i.e., one every 400 ft), 8-in. in diameter would be needed for a 10,000 ft pipe inspection. Table 5-24 estimates the site preparation costs based upon the required pothole excavations.

Table 5-22. Estimated Site Preparation Costs for Sahara® WTT Pipe Wall Survey of 10,000 ft pipe

| Cost Item | Set-up Costs | Quantity | Unit Cost | Unit | Total Cost |
|---|---|---|---|---|---|
| 1 | 2 – Rented 6 ft x 8 ft trench boxes | 2 boxes x 3 days = 6 days | $93.00 | 6 | $558.00 |
| 2 | 2-in. taps w/ valve and 150 lb standard flange with extension tube | 2 taps | $346.23 | 2 | $692.46 |
| 3 | 2 CY of stone backfill around the pipe | 2 CY | $46.50 | 2 | $93.00 |
| 4 | Traffic control | 1 person x 3 days^ x 8 hrs/day = 24 hrs | $50.00 | 24 | $1,200.00 |
| 5 | 3 Persons – Labor (excavate*, install taps, backfill, restoration) | 3 persons x 2 days x 8 hrs/day = 48 hrs | $52.70 | 48 | $2,529.60 |
| 6 | 1 Person – Equipment Operator (excavate*, remove plates, backfill) | 1 person x 2 days x 8 hrs/day = 16 hrs | $67.75 | 16 | $1,084.00 |
| 7 | 1 – 5/8 CY wheel mounted backhoe rental | 2 days | $215.00 | 2 | $430.00 |
| | | | | **Total** | **$6,587.06** |

^ Traffic control required during 2 days of site preparation and on the day of inspection.
* Excavation of 2 access pits 8 ft x 10 ft x 8 ft with trench boxes and 26 potholes (one every 400 ft) to position the sensor on top of the pipe would require 2 days.

Table 5-23. Estimated Site Preparation Costs for SmartBall™ Pipe Wall Survey of 10,000 ft pipe

| Cost Item | Set-up Costs | Quantity | Unit Cost | Unit | Total Cost |
|---|---|---|---|---|---|
| 1 | 2 – Rented 6 ft x 8 ft trench boxes | 2 boxes x 3 days = 6 days | $93.00 | 6 | $558.00 |
| 2 | 4-in. taps w/ valve and 150 lb standard flange with extension tube | 2 taps | $525.00 | 2 | $1,050.00 |
| 3 | 2 CY of stone backfill around the pipe | 2 CY | $46.50 | 2 | $93.00 |
| 4 | Traffic control | 1 person x 3 days^ x 8 hrs/day = 24 hrs | $50.00 | 24 | $1,200.00 |
| 5 | 3 Persons – Labor (excavate*, install taps, backfill, restoration) | 3 persons x 2 days x 8 hrs/day = 48 hrs | $52.70 | 48 | $2,529.60 |
| 6 | 1 Person – Equipment Operator (excavate*, remove plates, backfill) | 1 person x 2 days x 8 hrs/day = 16 hrs | $67.75 | 16 | $1,084.00 |
| 7 | 1 – 5/8 CY Wheel Mounted Backhoe | 2 days | $215.00 | 2 | $430.00 |
| | | | | **Total** | **$6,944.60** |

^ Traffic control required during 2 days of site preparation; and on the day of inspection.
* Excavation of 2 access pits 8 ft x 10 ft x 8 ft with trench boxes and 9 pits (one every 1,000 ft) to position the sensor on top of the pipe would require 2 days of work.

Table 5-24. Estimated Site Preparation Costs for ThicknessFinder Pipe Wall Survey of 10,000 ft pipe

| Cost Item | Set-up Costs | Quantity | Unit Cost | Unit | Total Cost |
|---|---|---|---|---|---|
| 1 | Traffic control | 1 person x 6 days^ x 8 hrs/day = 48 hrs | $50.00 | 48 | $2,400.00 |
| 2 | 1 Person – Labor (excavate*, backfill, restoration) | 1 person x 2 days x 8 hrs/day = 16 hrs | $52.70 | 16 | $843.20 |
| 3 | 1 Person – Equipment Operator (excavate*, remove plates, backfill) | 1 person x 2 days x 8 hrs/day = 16 hrs | $67.75 | 16 | $1084.00 |
| 4 | 1 – 5/8 CY Wheel Mounted Backhoe | 2 days | $215.00 | 2 | $430.00 |
| | | | | **Total** | **$4,757.20** |

^ Traffic control required during 2 days of site preparation and 4 days of inspection.

* Excavation of 26 potholes that are 8-in. in diameter (one every 400 ft) to position the sensor on top of the pipe would require 2 days (assuming 13 potholes/day).

**Internal Inspection Technologies.** Inspection costs were not provided for PipeDiver®, so site preparation costs are not estimated in this report.

For a See Snake® inspection, two 10 ft sections of pipe must be removed to allow for access and inspection. For purposes of this cost estimate, it is assumed that two required access points must be installed for a 10,000 ft pipe inspection. Table 5-25 estimates the site preparation costs based upon the required excavations for access for a See Snake® inspection.

Table 5-25. Estimated Site Preparation Costs for See Snake® Pipe Wall Survey of 10,000 ft pipe

| Cost Item | Set-up Costs | Quantity | Unit Cost | Unit | Total Cost |
|---|---|---|---|---|---|
| 1 | 2 – Rented 8 ft x 16 ft trench boxes | 2 boxes x 3 days = 6 days | $158.00 | 6 | $948.00 |
| 2 | 3 CY of stone backfill around the pipe | 3 CY | $46.50 | 3 | $139.50 |
| 3 | Traffic control | 1 person x 3 days^ x 8 hrs/day = 24 hrs | $50.00 | 24 | $1,200.00 |
| 4 | 3 Persons – Labor (excavate, backfill, restoration) | 3 persons x 1 day x 8 hrs/day = 24 hrs | $52.70 | 24 | $1,264.80 |
| 5 | 1 Person – Equipment Operator (excavate, remove plates, backfill, inspection) | 1 person x 3 days* x 8 hrs/day = 24 hrs | $67.75 | 24 | $1,626.00 |
| 6 | 1 – 5/8 CY wheel mounted backhoe rental | 3 days | $215.00 | 3 | $645.00 |
| | | | | **Total** | **$5,823.30** |

^ Traffic control required during 1 day of site preparation; and on 2 days of inspection.

* Operator required during 1 day of site preparation; and on 2 days of inspection.

**External Inspection Technologies.** For an AESL ECAT inspection, excavations with trench boxes are needed every 1,200 ft to access the pipe inspection. For purposes of this cost estimate, it is assumed that nine required access points must be installed for a 10,000 ft pipe inspection. Table 5-26 estimates the site preparation costs based upon the required excavations for an ECAT inspection.

Table 5-26. Estimated Site Preparation Costs for ECAT Pipe Wall Survey of 10,000 ft pipe

| Cost Item | Set-up Costs | Quantity | Unit Cost | Unit | Total Cost |
|---|---|---|---|---|---|
| 1 | 9 – Rented 6 ft x 8 ft trench boxes | 9 boxes x 4 days = 36 days | $93.00 | 36 | $3,348.00 |
| 2 | 9 CY of stone backfill around the pipe | 9 CY | $46.50 | 9 | $418.50 |
| 3 | Traffic control | 1 person x 4 days^ x 8 hrs/day = 32 hrs | $50.00 | 32 | $1,600.00 |
| 4 | 3 Persons – Labor (excavate*, backfill, restoration) | 3 persons x 2 days x 8 hrs/day = 48 hrs | $52.70 | 48 | $2,529.60 |
| 5 | 1 Person – Equipment Operator (excavate*, remove plates, backfill) | 1 person x 2 days x 8 hrs/day = 16 hrs | $67.75 | 16 | $1,084.00 |
| 6 | 1 – 5/8 CY wheel mounted backhoe rental | 2 days | $215.00 | 2 | $430.00 |
| | | | | **Total** | **$9,410.10** |

^ Traffic control required during 2 days of site preparation; and on 2 days of inspection, assuming 4 to 6 scans per day.

* Excavation of 9 access pits 8 ft x 8 ft x 8 ft with trench boxes (one every 1,200 ft) would require 2 days of work assuming 4 to 5 pits/day.

For an RSG HSK inspection, excavations with trench boxes are needed every 900 ft to access the pipe inspection. For purposes of this cost estimate, it is assumed that 13 required access points must be installed for a 10,000 ft pipe inspection (11 locations, plus 2 on either side of the railroad track as listed above). Table 5-27 estimates the site preparation costs based upon the required excavations for an HSK inspection. The site preparation costs for a CAP inspection are not provided as the vendor did not provide corresponding inspection costs.

Table 5-27. Estimated Site Preparation Costs for HSK Pipe Wall Survey of 10,000 ft pipe

| Cost Item | Set-up Costs | Quantity | Unit Cost | Unit | Total Cost |
|---|---|---|---|---|---|
| 1 | 13 – Rented 6 ft x 8 ft trench boxes | 13 boxes x 6 days = 78 days | $93.00 | 78 | $7,254.00 |
| 2 | 13 CY of stone backfill around the pipe | 13 CY | $46.50 | 13 | $604.50 |
| 3 | Traffic control | 1 person x 6 days^ x 8 hrs/day = 48 hrs | $50.00 | 48 | $2,400.00 |
| 4 | 3 Persons – Labor (excavate*, backfill, restoration) | 3 persons x 3 days x 8 hrs/day = 72 hrs | $52.70 | 72 | $3,794.40 |
| 5 | 1 Person – Equipment Operator (excavate*, remove plates, backfill) | 1 person x 3 days x 8 hrs/day = 24 hrs | $67.75 | 24 | $1,626.00 |
| 6 | 1 – 5/8 CY wheel mounted backhoe rental | 3 days | $215.00 | 3 | $645.00 |
| | | | | **Total** | **$16,323.90** |

^ Traffic control required during 3 days of site preparation; and on 3 days of inspection, assuming 4 to 5 scans per day.

* Excavation of 13 access pits 8 ft x 8 ft x 8 ft with trench boxes (one every 900 ft) would require 3 days of work assuming 4 to 5 pits/day.

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FINAL REPORT

# FIELD DEMONSTRATION OF INNOVATIVE CONDITION ASSESSMENT TECHNOLOGIES FOR WATER MAINS: ACOUSTIC PIPE WALL ASSESSMENT, INTERNAL INSPECTION, AND EXTERNAL INSPECTION

## VOLUME 2: APPENDICES (A-H)

by

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**Contract No. EP-C-05-057**
**Task Order No. 0062**

for

**Michael Royer**
**Task Order Manager**

**Water Supply and Water Resources Division**
**National Risk Management Research Laboratory**
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**National Risk Management Research Laboratory**
**Office of Research and Development**
**U.S. Environmental Protection Agency**
**Cincinnati, Ohio 45268**

**July 2013**

# VOLUME 2
# CONTENTS

## APPENDICES

# APPENDIX A

## Assessment Data for Excavated Pipe

# CONTENTS

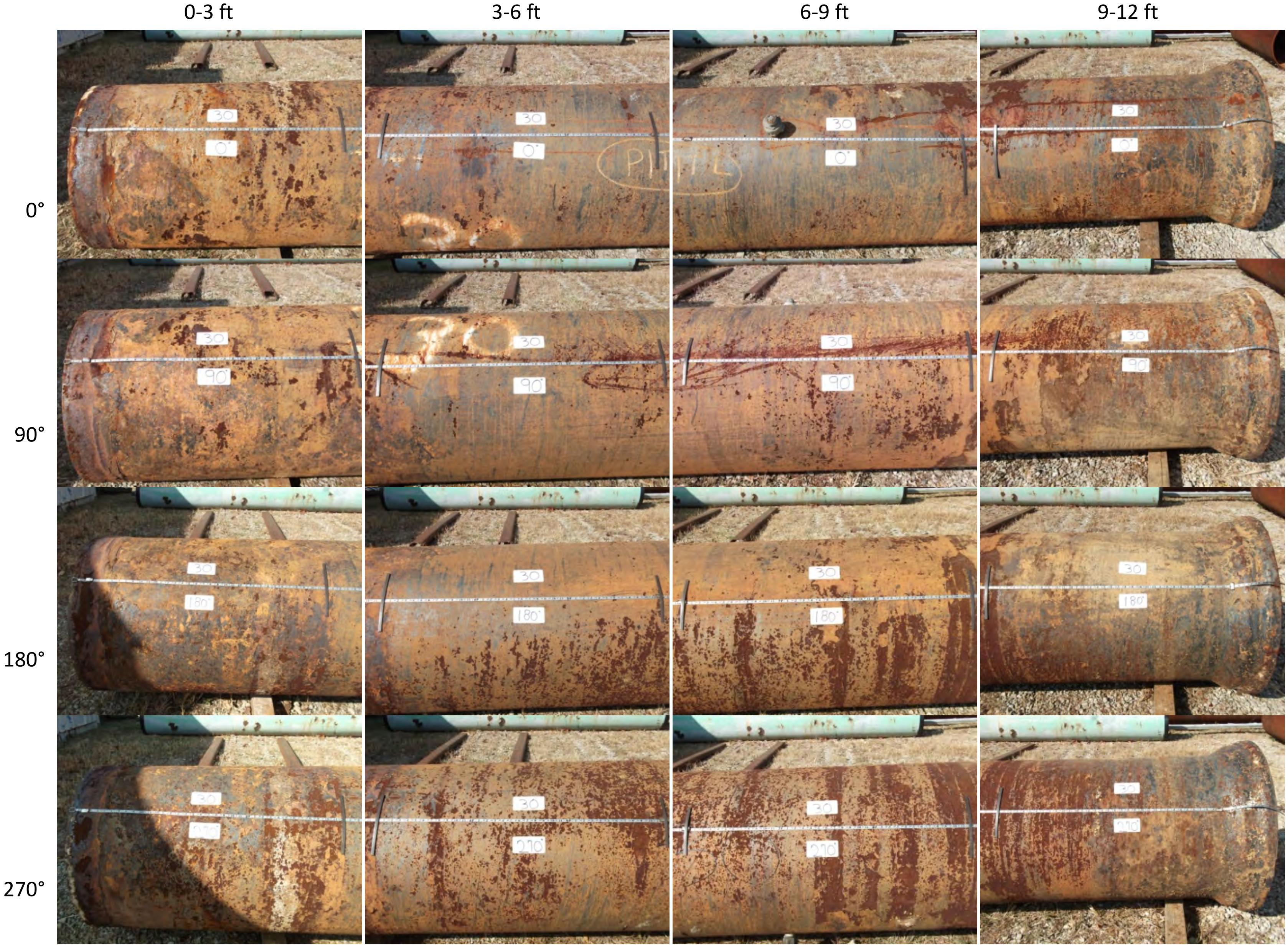


Figure A-30(1). Pipe 30 as Removed from Site

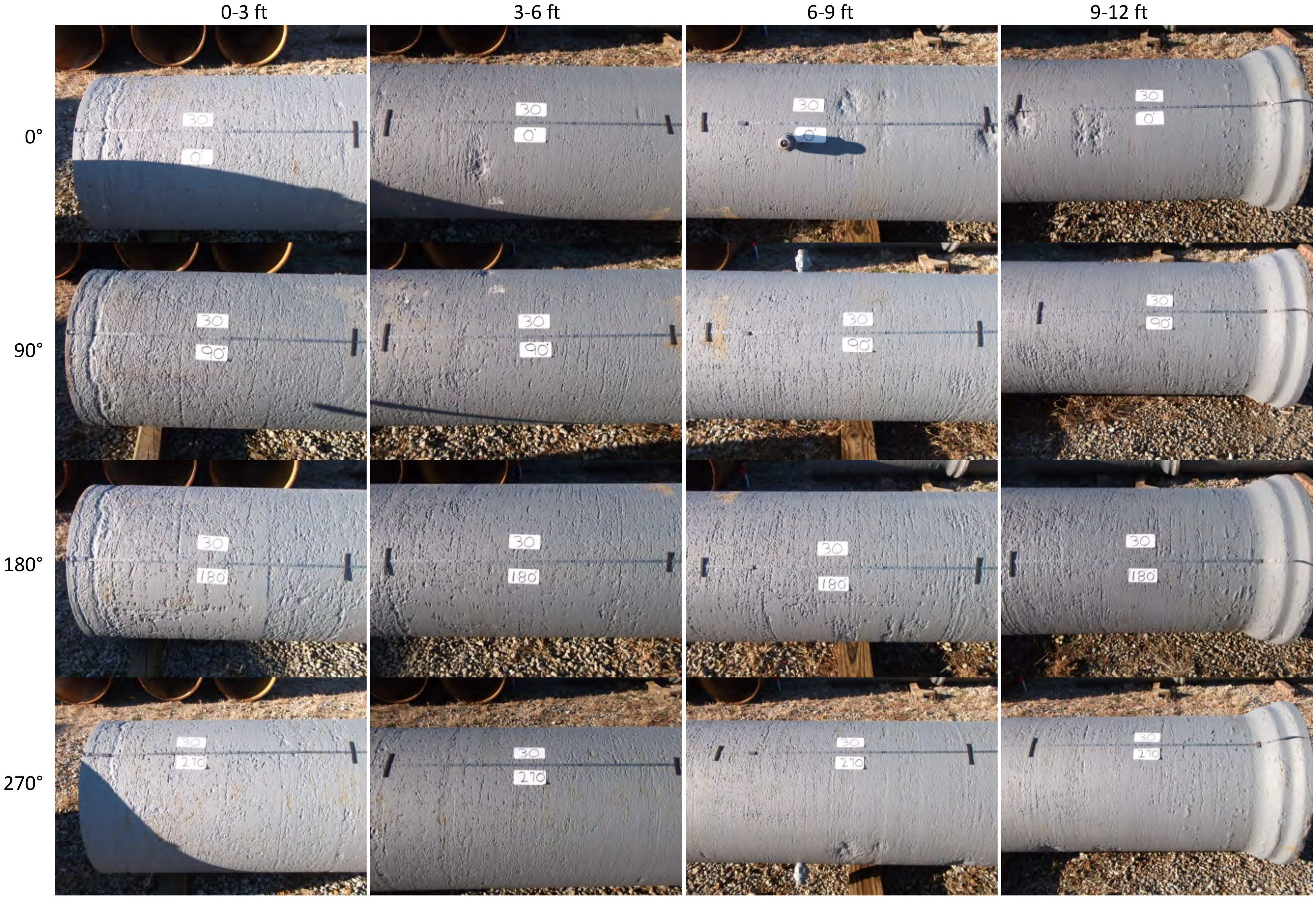


Figure A-30(2). Pipe 30 after Sandblasting

### Table A-30(1). Wall Thickness of Cast Iron at Spigot with Caliper

| | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| Pipe Number | 0° | 180° | 220° | 240° |
| 30 | 0.781 | 0.784 | 0.790 | 0.776 |

### Table A-30(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)

| | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| Pipe Number | Caliper | UT | | | UT | | | UT | | |
| 30 | 0.766 | 0.782 | 0.779 | 0.799 | 0.750 | 0.754 | 0.750 | 0.805 | 0.831 | 0.807 |
| | 0.766 | 0.771 | 0.771 | 0.768 | 0.730 | 0.743 | 0.752 | 0.809 | 0.807 | 0.799 |
| | 0.780 | 0.769 | 0.797 | 0.785 | 0.750 | 0.758 | 0.753 | 0.793 | 0.812 | 0.809 |
| **Average** | 0.771 | 0.780 | | | 0.749 | | | 0.808 | | |
| **Standard Deviation** | 0.008 | 0.012 | | | 0.008 | | | 0.010 | | |
| **Minimum** | 0.766 | 0.768 | | | 0.730 | | | 0.793 | | |
| **Maximum** | 0.780 | 0.799 | | | 0.758 | | | 0.831 | | |
| **Repeat Center Cell** | - | 0.785 | | | 0.745 | | | 0.788 | | |

### Table A-30(3). Outer Diameter Measurement Using a pi Tape

| Pipe Number | Outer Diameter | | |
|---|---|---|---|
| | Spigot | Center | Bell |
| 30 | 25.835 | 25.812 | 25.817 |

### Table A-30(4). Wall Thickness of Cement Liner at Spigot with Caliper

| Measurement (Inches) | 0° | 180° | 220° | 240° |
|---|---|---|---|---|
| **Cast Iron** | 0.781 | 0.784 | 0.790 | 0.776 |
| **Cast Iron & Cement Liner** | 1.113 | 0.953 | 0.933 | 0.982 |
| **Cement Liner** | 0.332 | 0.169 | 0.143 | 0.206 |

### Table A-30(5). Pipe 30 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Bell (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| 030-114-336-010-040 | 3.5 | 32.0 | 0.279 | 36% | 0.50 | 64% | 2 | 0:04 |
| | | 34.5 | 0.217 | 28% | 0.56 | 72% | 2 | 0:04 |
| | | 31.0 | 0.198 | 25% | 0.58 | 75% | 13 | 0:26 |
| | | 32.0 | 0.173 | 22% | 0.61 | 78% | 355 | 11:50 |
| 030-104-328-010-041 | 7.3 | 42.0 | 0.531 | 68% | 0.25 | 32% | 10 | 0:20 |
| | | 40.5 | 0.276 | 35% | 0.50 | 65% | 16 | 0:32 |
| 030-087-308-011-047 | 5.9 | 60.0 | 0.367 | 47% | 0.41 | 53% | 30 | 1:00 |
| | | 58.5 | 0.257 | 33% | 0.52 | 67% | 36 | 1:12 |
| | | 54.5 | 0.185 | 24% | 0.60 | 76% | 39 | 1:18 |
| 030-045-340-007-042 | 3.9 | 102.0 | 0.362 | 46% | 0.42 | 54% | 353 | 11:46 |

20.7

Figure A-30(1). Pipe 30, area 030-114-336-010-040

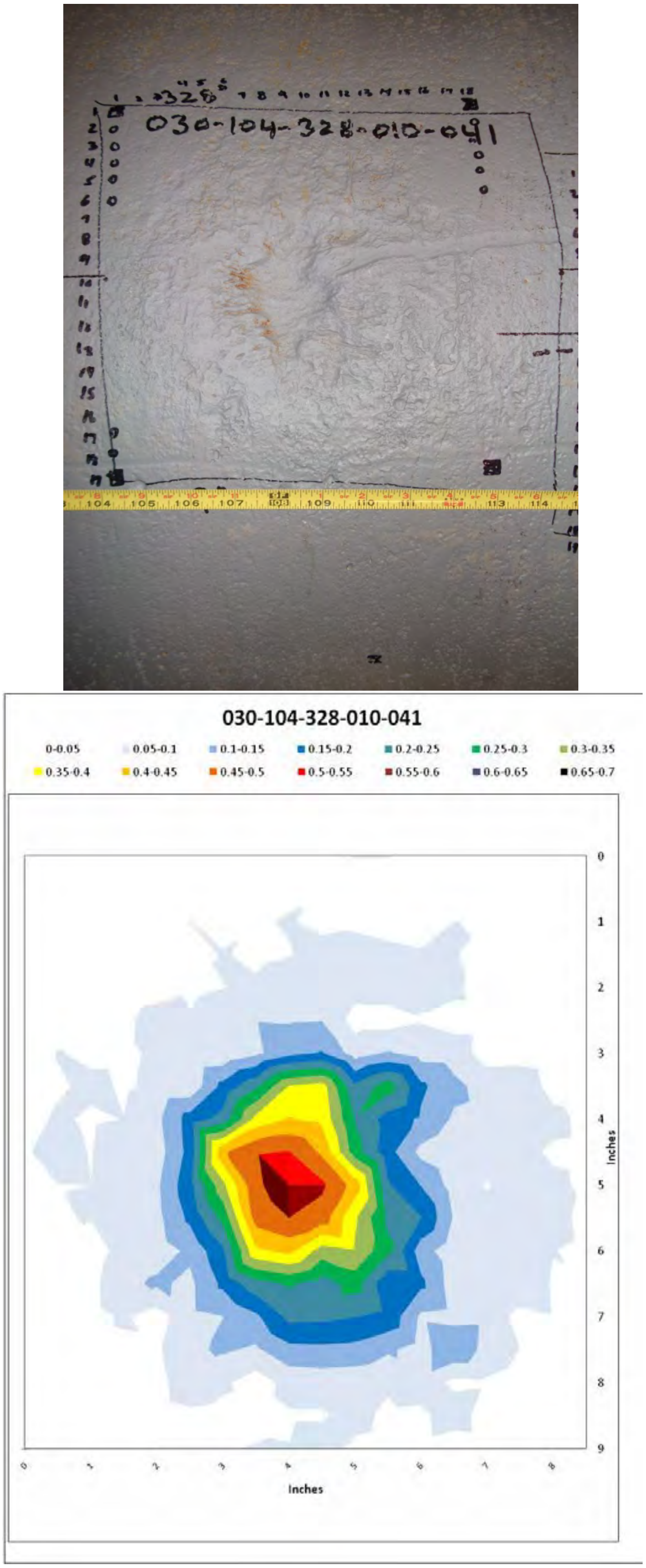


Figure A-30(2). Pipe 30, area 030-104-328-010-041

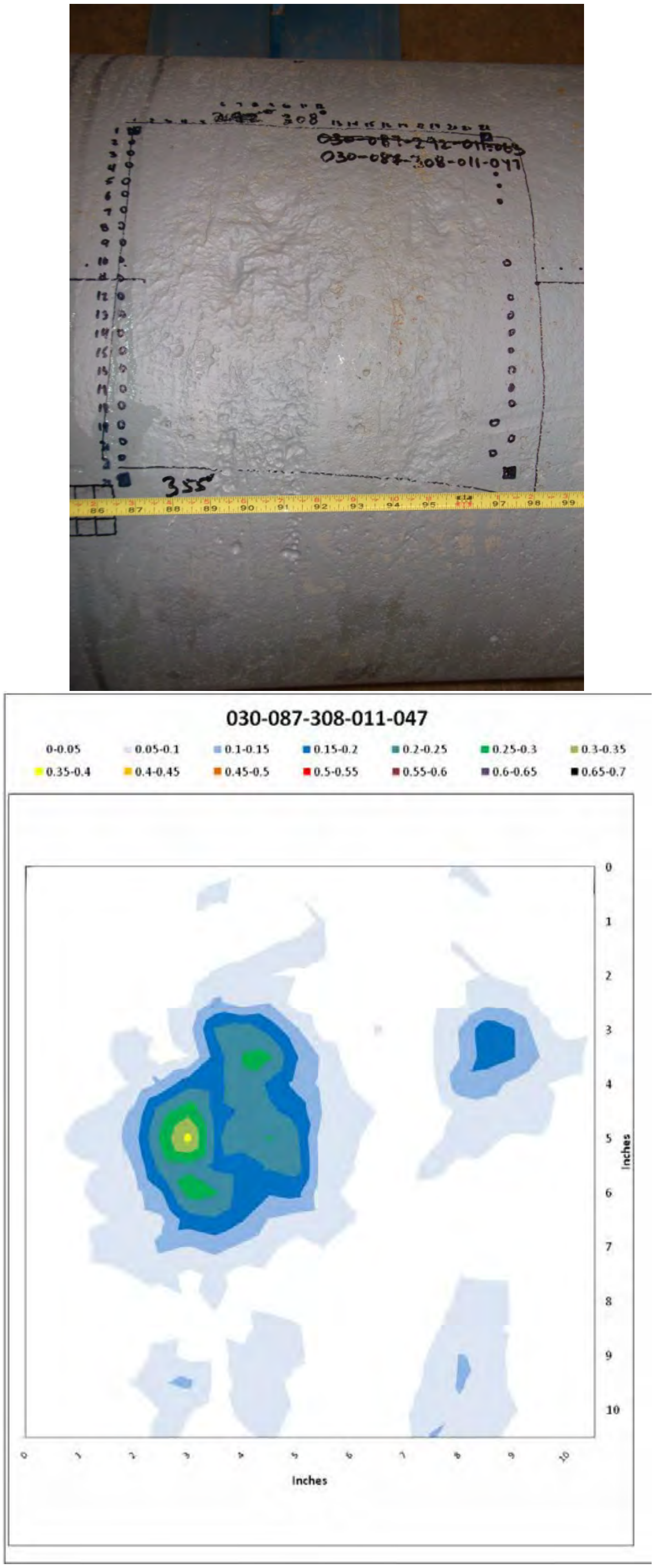


**Figure A-30(3). Pipe 30, area 030-087-308-011-047**

**Figure A-30(4). Pipe 30, area 030-045-340-007-042**

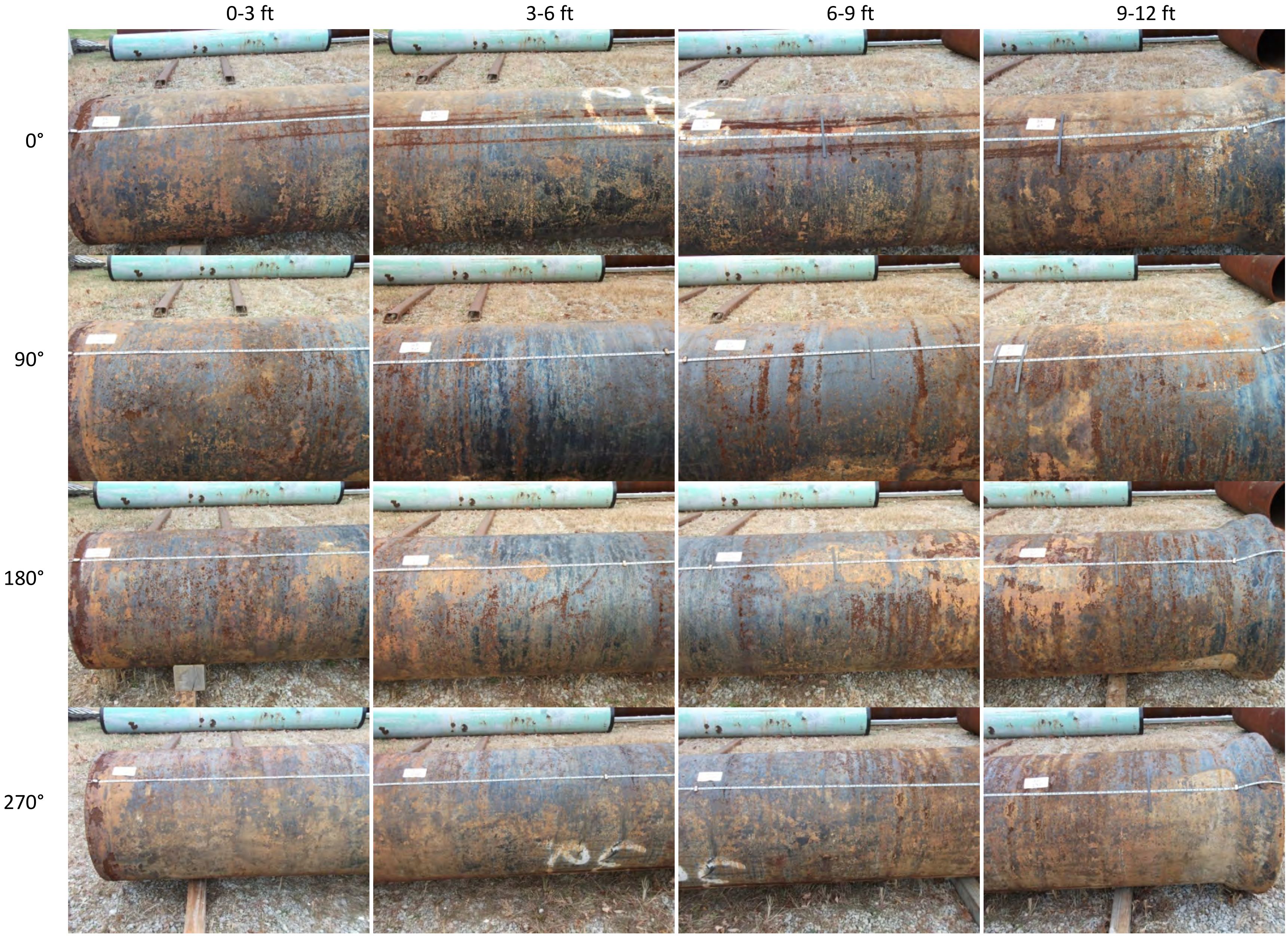


Figure A-32(1). Pipe 32 as Removed from Site

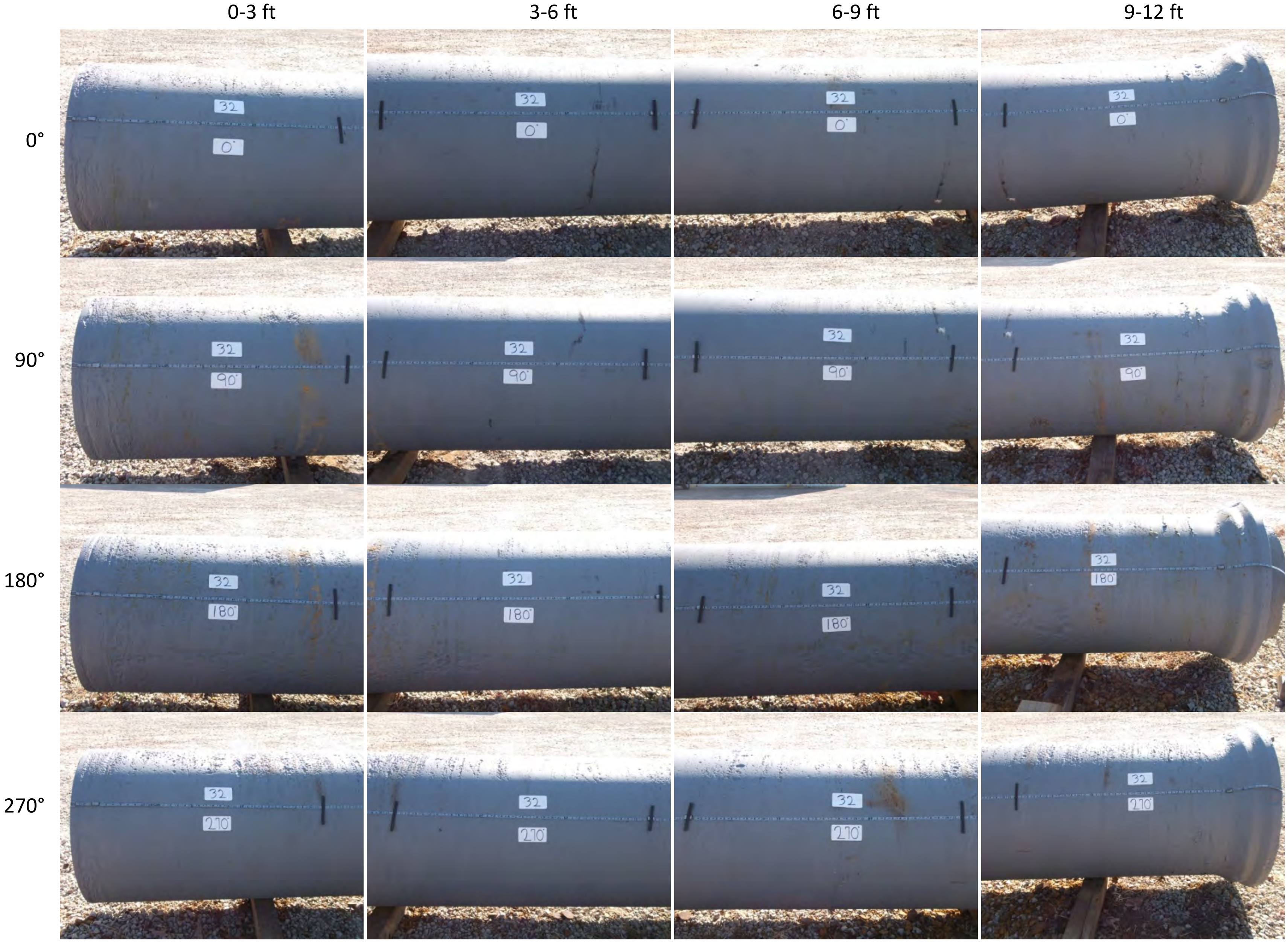


Figure A-32(2). Pipe 32 after Sandblasting

**Table A-32(1). Wall Thickness of Cast Iron at Spigot with Caliper**

| | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| **Pipe Number** | **140°** | **190°** | **270°** | **310°** |
| 32 | 0.806 | 0.803 | 0.805 | 0.796 |

**Table A-32(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)**

| | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Spigot** | | | | **Center** | | | **Bell** | | |
| **Pipe Number** | **Caliper** | **UT** | | | **UT** | | | **UT** | | |
| 32 | 0.817 | 0.777 | 0.781 | 0.783 | 0.772 | 0.782 | 0.775 | 0.815 | 0.813 | 0.811 |
| | 0.818 | 0.784 | 0.788 | 0.780 | 0.771 | 0.777 | 0.782 | 0.809 | 0.831 | 0.817 |
| | 0.797 | 0.777 | 0.785 | 0.784 | 0.773 | 0.775 | 0.780 | 0.815 | 0.821 | x |
| **Average** | 0.811 | 0.782 | | | 0.776 | | | 0.817 | | |
| **Standard Deviation** | 0.012 | 0.004 | | | 0.004 | | | 0.007 | | |
| **Minimum** | 0.797 | 0.777 | | | 0.771 | | | 0.809 | | |
| **Maximum** | 0.818 | 0.788 | | | 0.782 | | | 0.831 | | |
| **Repeat Center Cell** | - | 0.786 | | | 0.777 | | | 0.818 | | |

**Table A-32(3). Outer Diameter Measurement Using a pi Tape**

| | Outer Diameter | | |
|---|---|---|---|
| **Pipe Number** | **Spigot** | **Center** | **Bell** |
| 32 | 25.830 | 25.870 | 25.834 |

**Table A-32(4). Wall Thickness of Cement Liner at Spigot with Caliper**

| Measurement (Inches) | 140° | 190° | 270° | 310° |
|---|---|---|---|---|
| **Cast Iron** | 0.806 | 0.803 | 0.805 | 0.796 |
| **Cast Iron & Cement Liner** | 1.091 | 1.053 | 1.137 | 1.102 |
| **Cement Liner** | 0.285 | 0.250 | 0.332 | 0.306 |

### Table A-32(5). Pipe 32 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Bell (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| 032-082-145-039-050 | 32.3 | 51.5 | 0.620 | 79% | 0.16 | 21% | 180 | 6:00 |
| | | 51.0 | 0.474 | 61% | 0.31 | 39% | 188 | 6:16 |
| | | 43.5 | 0.434 | 56% | 0.35 | 44% | 182 | 6:04 |
| | | 65.5 | 0.379 | 49% | 0.40 | 51% | 202 | 6:44 |
| | | 46.0 | 0.366 | 47% | 0.41 | 53% | 180 | 6:00 |
| | | 48.5 | 0.355 | 46% | 0.43 | 54% | 184 | 6:08 |
| | | 61.5 | 0.353 | 45% | 0.43 | 55% | 180 | 6:00 |
| | | 60.5 | 0.341 | 44% | 0.44 | 56% | 186 | 6:12 |
| | | 36.5 | 0.288 | 37% | 0.49 | 63% | 186 | 6:12 |
| | | 67.0 | 0.269 | 34% | 0.51 | 66% | 195 | 6:30 |
| | | 59.0 | 0.269 | 34% | 0.51 | 66% | 180 | 6:00 |
| | | 40.5 | 0.263 | 34% | 0.52 | 66% | 180 | 6:00 |
| | | 45.0 | 0.260 | 33% | 0.52 | 67% | 191 | 6:22 |
| | | 62.5 | 0.253 | 32% | 0.53 | 68% | 197 | 6:34 |
| | | 66.0 | 0.249 | 32% | 0.53 | 68% | 191 | 6:22 |
| | | 58.0 | 0.246 | 31% | 0.53 | 69% | 182 | 6:04 |
| | | 61.5 | 0.243 | 31% | 0.54 | 69% | 195 | 6:30 |
| | | 39.0 | 0.220 | 28% | 0.56 | 72% | 188 | 6:16 |
| | | 33.5 | 0.208 | 27% | 0.57 | 73% | 184 | 6:08 |
| 032-017-118-032-119 | 34.3 | 128.5 | 0.333 | 43% | 0.45 | 57% | 187 | 6:14 |
| | | 129.5 | 0.276 | 35% | 0.50 | 65% | 184 | 6:08 |
| | | 129.5 | 0.250 | 32% | 0.53 | 68% | 189 | 6:18 |
| | | 125.5 | 0.237 | 30% | 0.54 | 70% | 182 | 6:04 |
| | | 130.0 | 0.228 | 29% | 0.55 | 71% | 178 | 5:56 |
| | | 115.5 | 0.225 | 29% | 0.56 | 71% | 149 | 4:58 |
| | | 117.0 | 0.221 | 28% | 0.56 | 72% | 142 | 4:44 |
| | | 111.5 | 0.216 | 28% | 0.56 | 72% | 215 | 7:10 |

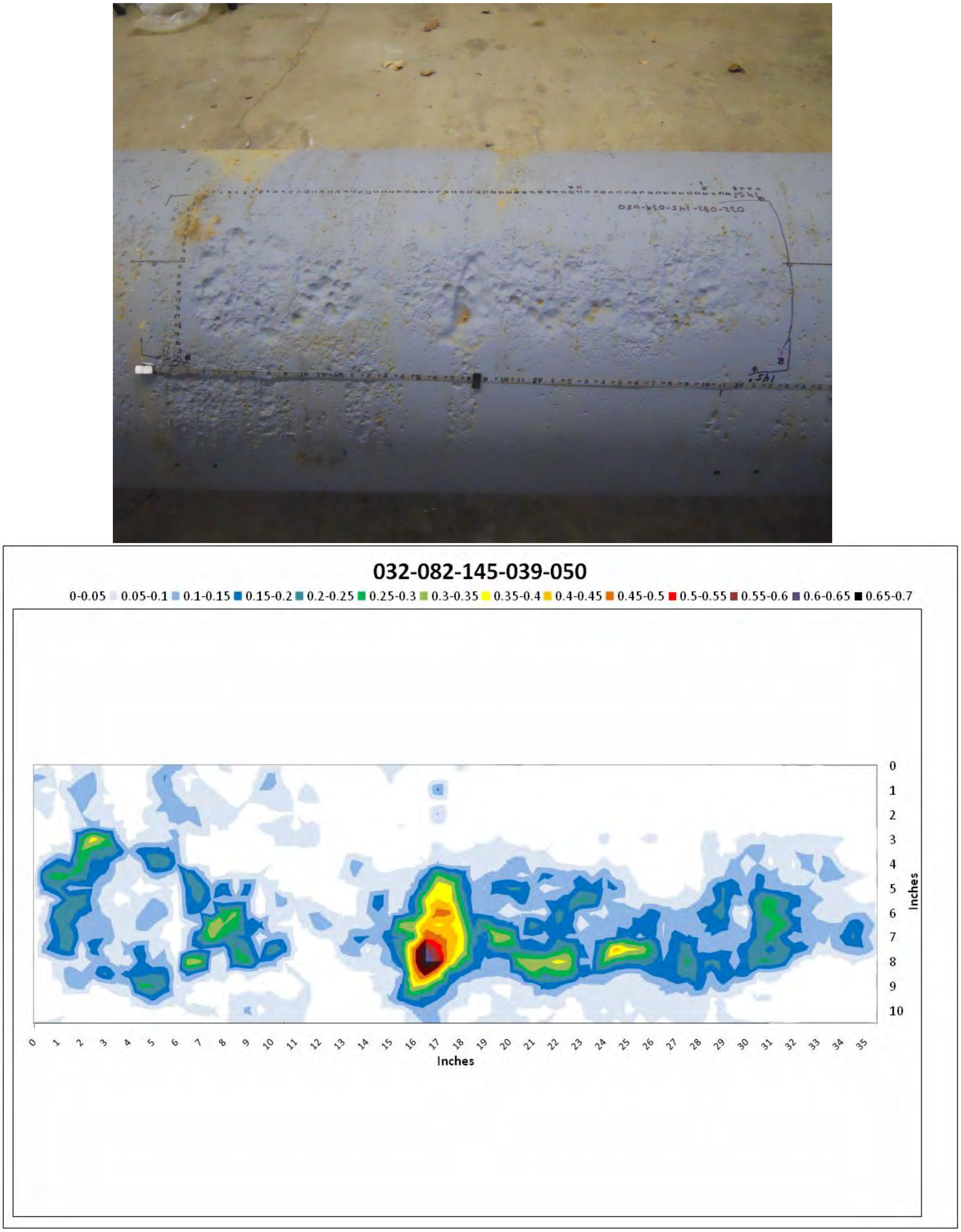


Figure A-32(1). Pipe 32, area 032-082-145-039-050

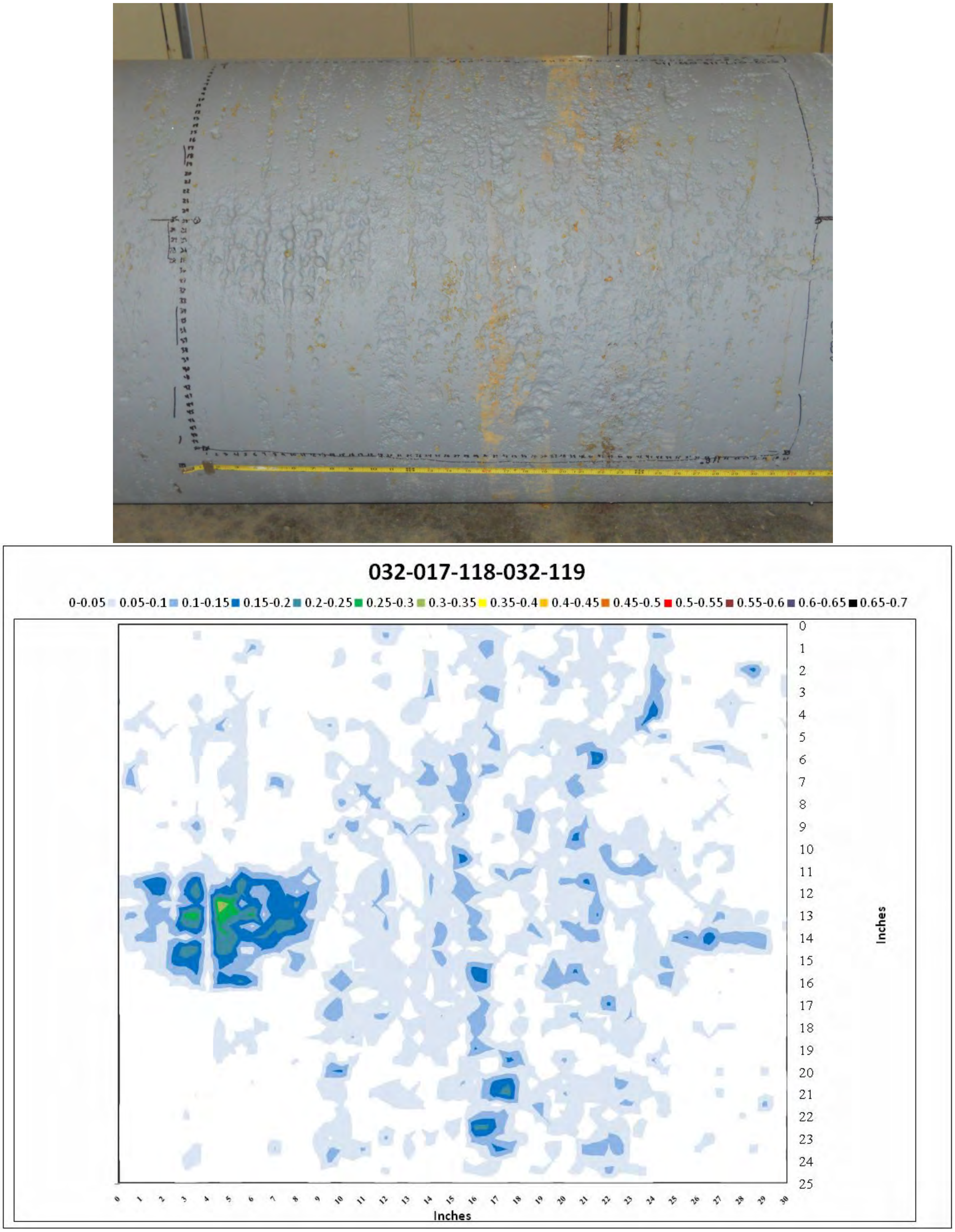


Figure A-32(2). Pipe 32, area 032-017-118-032-119

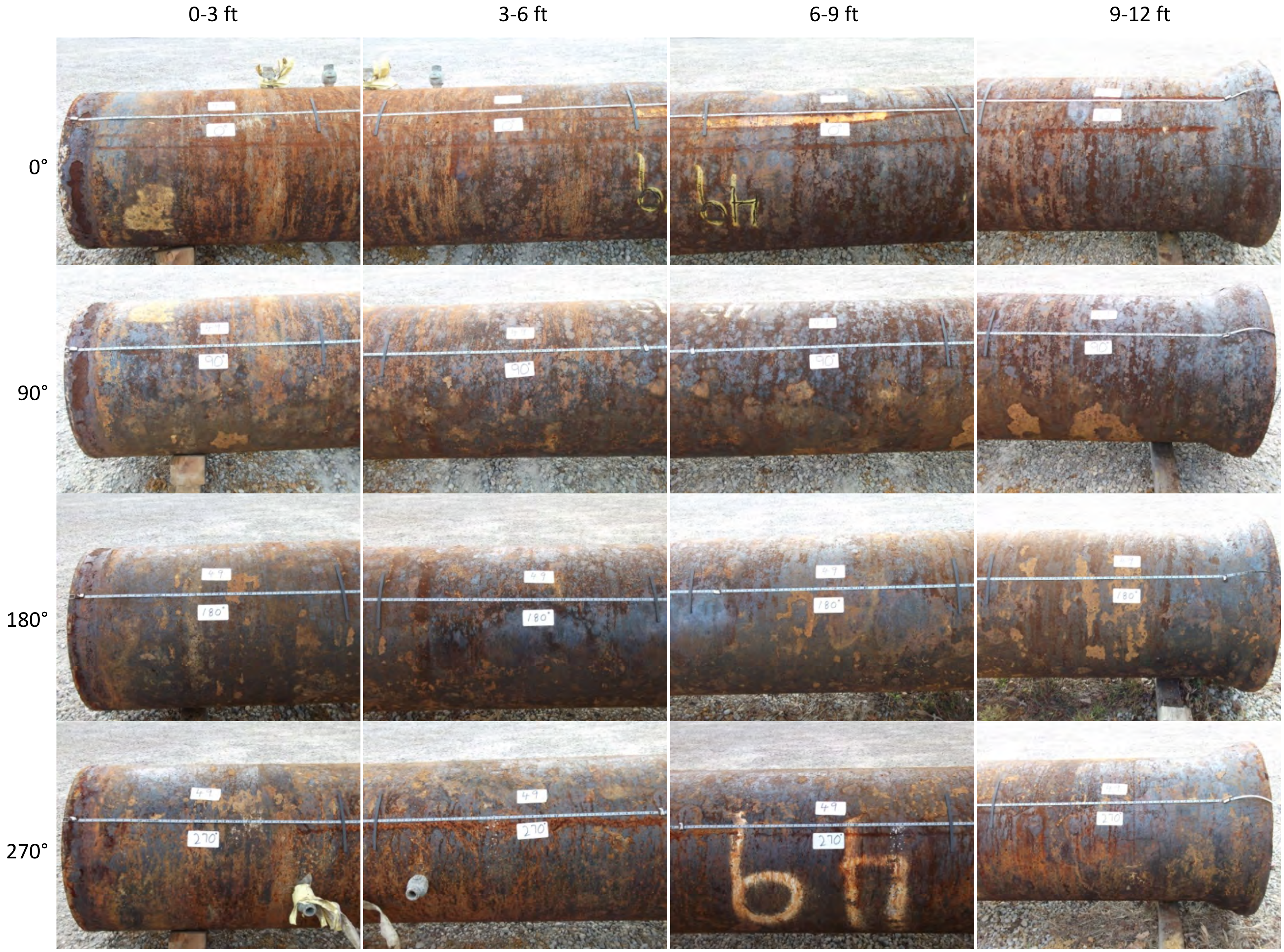


Figure A-49(1). Pipe 49 as Removed from Site

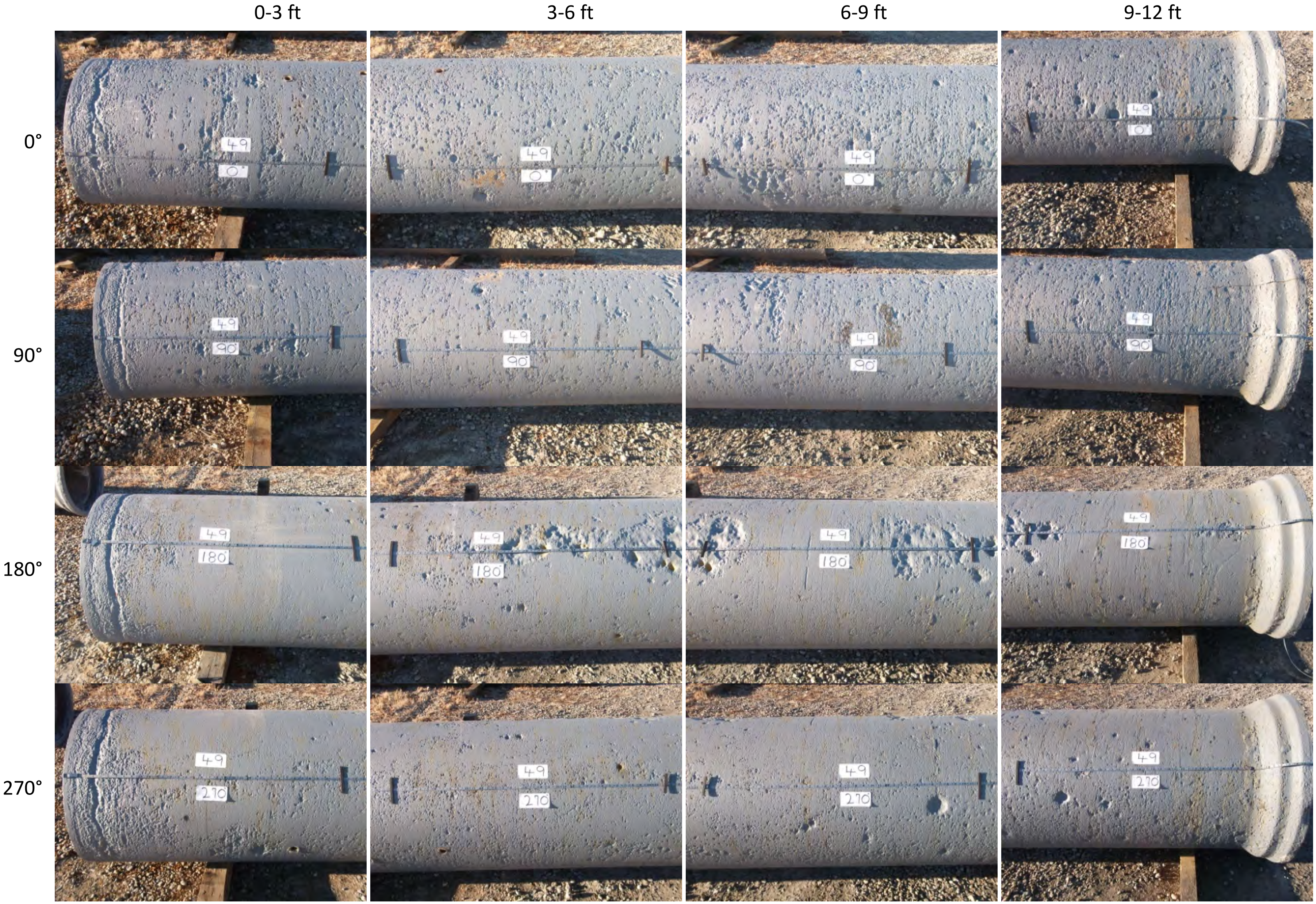


Figure A-49(2). Pipe 49 after Sandblasting

Table A-49(1). Wall Thickness of Cast Iron at Spigot with Caliper

| Pipe Number | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| | 125° | 145° | 155° | 200° |
| 49 | 0.782 | 0.786 | 0.806 | 0.798 |

Table A-49(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)

| Pipe Number | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| | Caliper | UT | | | UT | | | UT | | |
| 49 | 0.789 | 0.779 | 0.804 | 0.802 | 0.776 | 0.788 | 0.776 | 0.783 | 0.782 | 0.737 |
| | 0.794 | 0.802 | 0.804 | 0.807 | 0.778 | 0.786 | 0.776 | 0.746 | 0.743 | 0.753 |
| | 0.785 | 0.789 | 0.785 | 0.786 | 0.795 | 0.798 | 0.780 | 0.758 | 0.747 | 0.740 |
| **Average** | 0.789 | 0.795 | | | 0.784 | | | 0.754 | | |
| **Standard Deviation** | 0.005 | 0.010 | | | 0.009 | | | 0.017 | | |
| **Minimum** | 0.785 | 0.779 | | | 0.776 | | | 0.737 | | |
| **Maximum** | 0.794 | 0.807 | | | 0.798 | | | 0.783 | | |
| **Repeat Center Cell** | - | 0.810 | | | 0.785 | | | 0.740 | | |

Table A-49(3). Outer Diameter Measurement Using a pi Tape

| Pipe Number | Outer Diameter | | |
|---|---|---|---|
| | Spigot | Center | Bell |
| 49 | 25.840 | 25.835 | 25.805 |

Table A-49(4). Wall Thickness of Cement Liner at Spigot with Caliper

| Measurement (Inches) | 125° | 145° | 155° | 200° |
|---|---|---|---|---|
| **Cast Iron** | 0.782 | 0.786 | 0.806 | 0.798 |
| **Cast Iron & Cement Liner** | 0.974 | 0.966 | 0.979 | 0.969 |
| **Cement Liner** | 0.192 | 0.180 | 0.173 | 0.171 |

## Table 49-5. Pipe 49 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Bell (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| 049-095-151-020-056 | 21.5 | 39.5 | 0.563 | 72% | 0.22 | 28% | 182 | 6:04 |
| | | 43.5 | 0.418 | 54% | 0.36 | 46% | 182 | 6:04 |
| | | 44.5 | 0.417 | 53% | 0.36 | 47% | 185 | 6:10 |
| | | 41.0 | 0.412 | 53% | 0.37 | 47% | 165 | 5:30 |
| | | 50.5 | 0.394 | 50% | 0.39 | 50% | 191 | 6:22 |
| | | 51.0 | 0.387 | 50% | 0.39 | 50% | 174 | 5:48 |
| | | 52.5 | 0.364 | 47% | 0.42 | 53% | 185 | 6:10 |
| | | 47.0 | 0.361 | 46% | 0.42 | 54% | 191 | 6:22 |
| | | 45.0 | 0.340 | 44% | 0.44 | 56% | 191 | 6:22 |
| | | 48.0 | 0.294 | 38% | 0.49 | 62% | 191 | 6:22 |
| | | 42.0 | 0.265 | 34% | 0.52 | 66% | 185 | 6:10 |
| 049-047-145-031-053 | 32.5 | 94.5 | 0.664 | 85% | 0.12 | 15% | 186 | 6:12 |
| | | 90.0 | 0.596 | 76% | 0.18 | 24% | 186 | 6:12 |
| | | 83.0 | 0.592 | 76% | 0.19 | 24% | 180 | 6:00 |
| | | 78.0 | 0.592 | 76% | 0.19 | 24% | 173 | 5:46 |
| | | 77.0 | 0.561 | 72% | 0.22 | 28% | 197 | 6:34 |
| | | 79.0 | 0.523 | 67% | 0.26 | 33% | 175 | 5:50 |
| | | 98.5 | 0.510 | 65% | 0.27 | 35% | 188 | 6:16 |
| | | 99.5 | 0.508 | 65% | 0.27 | 35% | 185 | 6:10 |
| | | 77.5 | 0.443 | 57% | 0.34 | 43% | 188 | 6:16 |
| | | 93.0 | 0.410 | 53% | 0.37 | 47% | 199 | 6:38 |
| | | 74.5 | 0.401 | 51% | 0.38 | 49% | 197 | 6:34 |
| | | 82.0 | 0.365 | 47% | 0.42 | 53% | 188 | 6:16 |
| 049-014-059-020-062 | 11.1 | 121.5 | 0.362 | 46% | 0.42 | 54% | 243 | 8:06 |
| | | 119.5 | 0.325 | 42% | 0.46 | 58% | 288 | 9:36 |
| | | 134.0 | 0.228 | 29% | 0.55 | 71% | 266 | 8:52 |
| | | 124.5 | 0.213 | 27% | 0.57 | 73% | 283 | 9:26 |
| | | 134.0 | 0.200 | 26% | 0.58 | 74% | 285 | 9:30 |
| 049-074-355-010-065 | 8.8 | 70.5 | 0.261 | 33% | 0.52 | 67% | 343 | 11:26 |
| | | 68.0 | 0.233 | 30% | 0.55 | 70% | 341 | 11:22 |
| | | 72.5 | 0.227 | 29% | 0.55 | 71% | 336 | 11:12 |
| | | 71.5 | 0.217 | 28% | 0.56 | 72% | 345 | 11:30 |
| | | 67.5 | 0.211 | 27% | 0.57 | 73% | 332 | 11:04 |
| 049-113-336-012-043 | 8.8 | 28.0 | 0.546 | 70% | 0.23 | 30% | 2 | 0:04 |
| | | 34.0 | 0.409 | 52% | 0.37 | 48% | 11 | 0:22 |
| | | 31.5 | 0.341 | 44% | 0.44 | 56% | 6 | 0:12 |
| | | 34.5 | 0.217 | 28% | 0.56 | 72% | 22 | 0:44 |
| 049-100-260-018-051 | 8.5 | 36.0 | 0.466 | 60% | 0.31 | 40% | 87 | 2:54 |
| | | 47.5 | 0.432 | 55% | 0.35 | 45% | 93 | 3:06 |
| | | 46.5 | 0.249 | 32% | 0.53 | 68% | 58 | 1:56 |
| | | 44.0 | 0.191 | 24% | 0.59 | 76% | 80 | 2:40 |
| 049-011-299-011-035 | 4.7 | 130.5 | 0.310 | 40% | 0.47 | 60% | 52 | 1:44 |
| | | 134.0 | 0.276 | 35% | 0.50 | 65% | 34 | 1:08 |
| | | 131.0 | 0.260 | 33% | 0.52 | 67% | 48 | 1:36 |
| | | 138.0 | 0.173 | 22% | 0.61 | 78% | 50 | 1:40 |

95.9

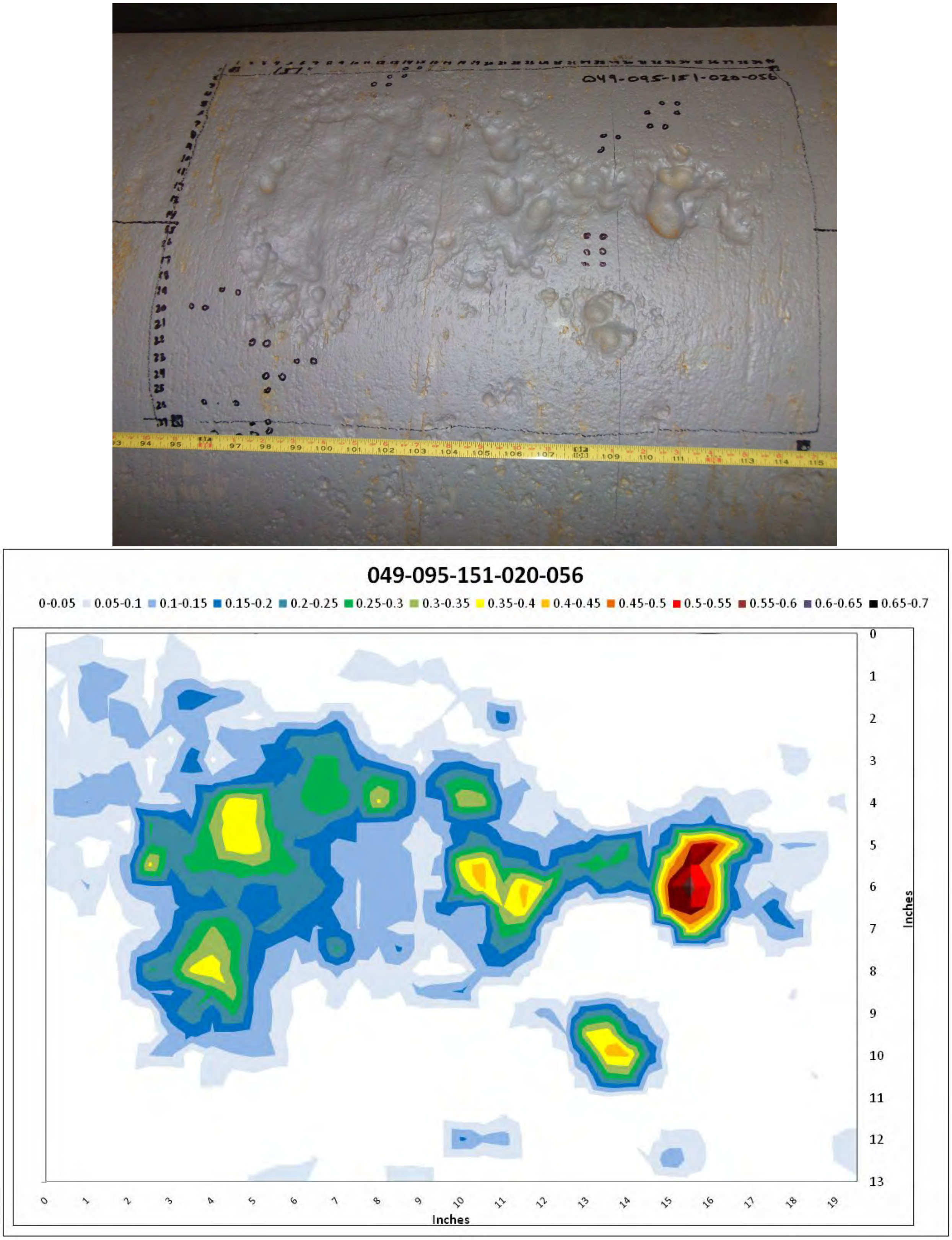


Figure A-49(1). Pipe 49, area 049-095-151-020-056

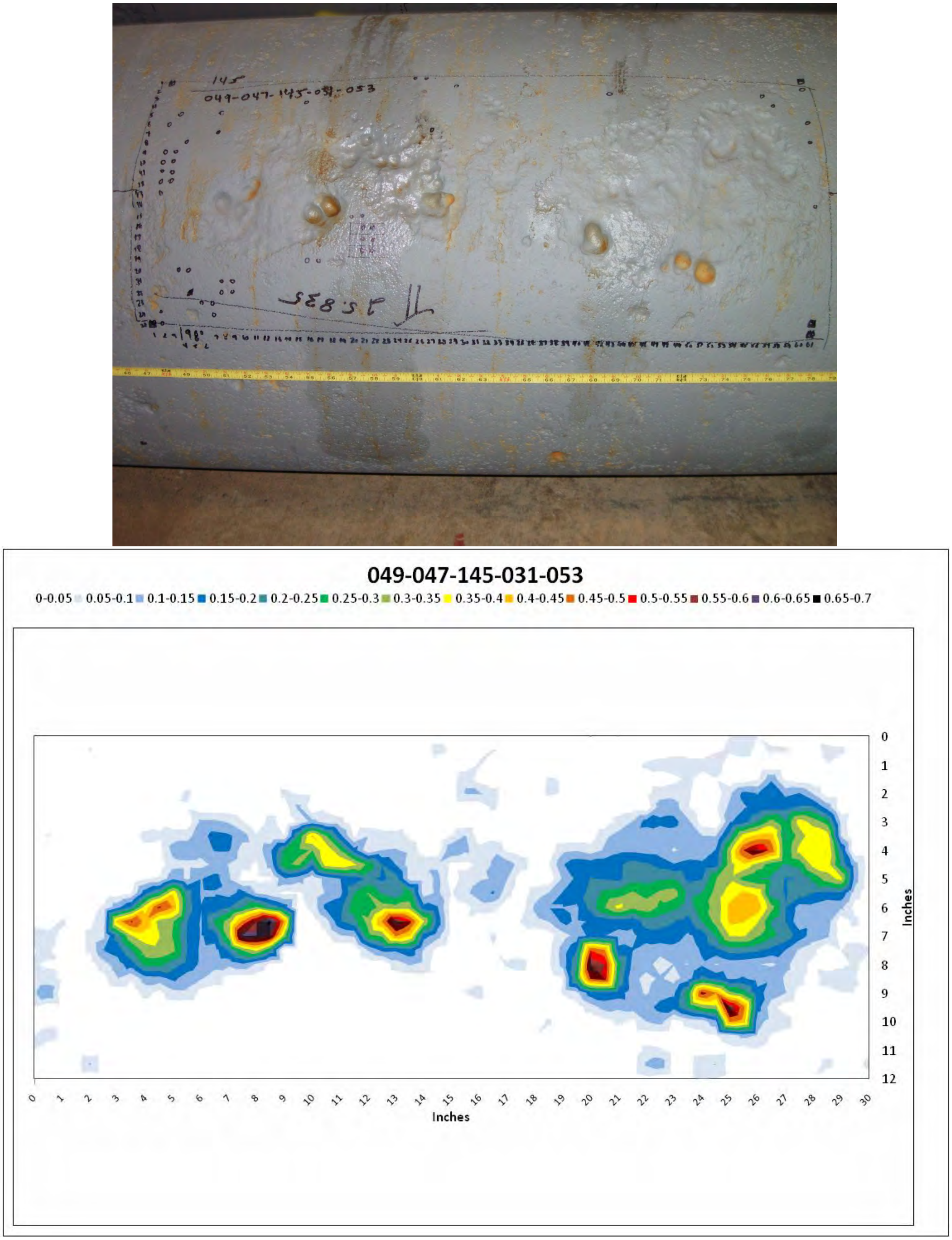


Figure A-49(2). Pipe 49, area 049-047-145-031-053

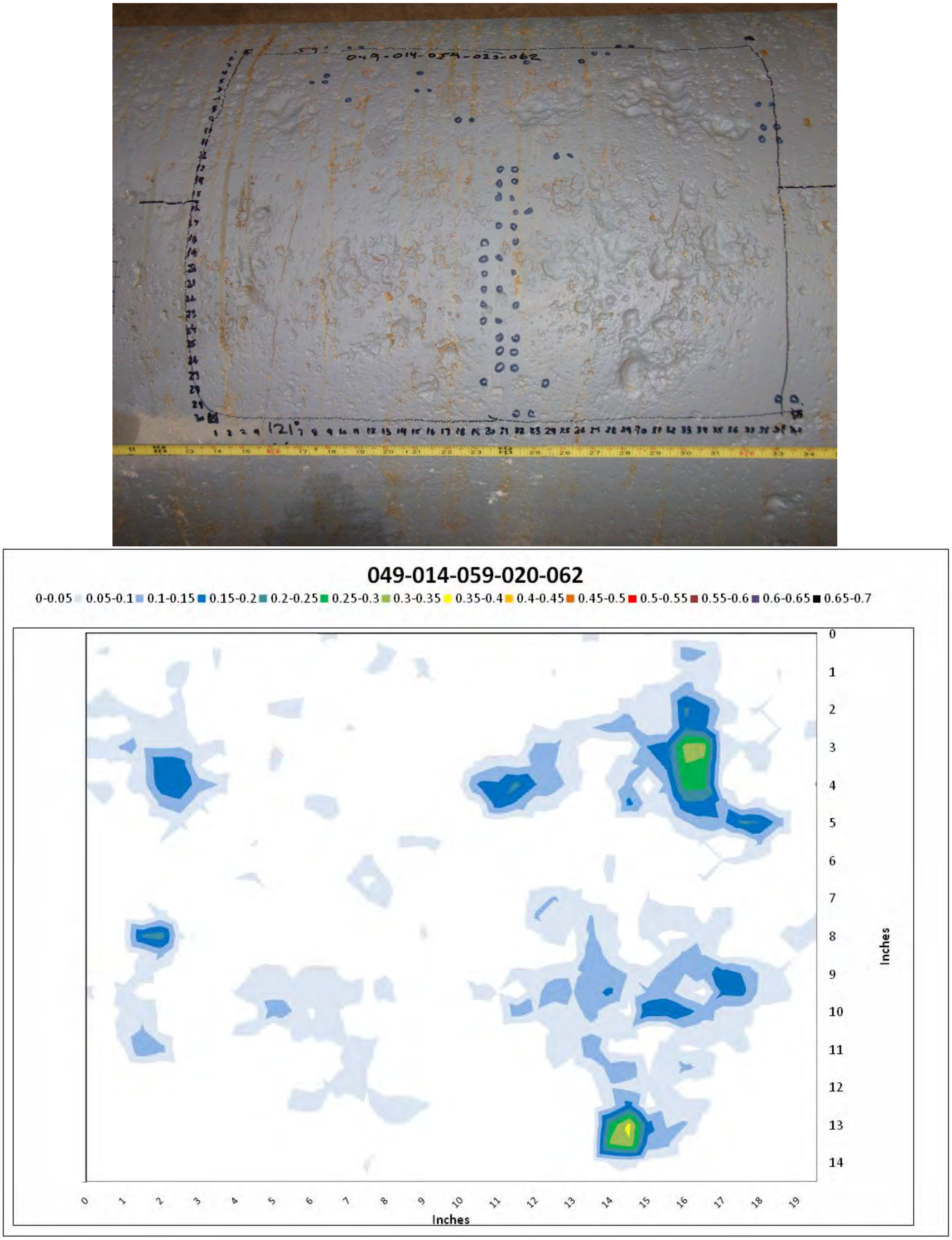


Figure A-49(3). Pipe 49, area 049-014-059-020-062

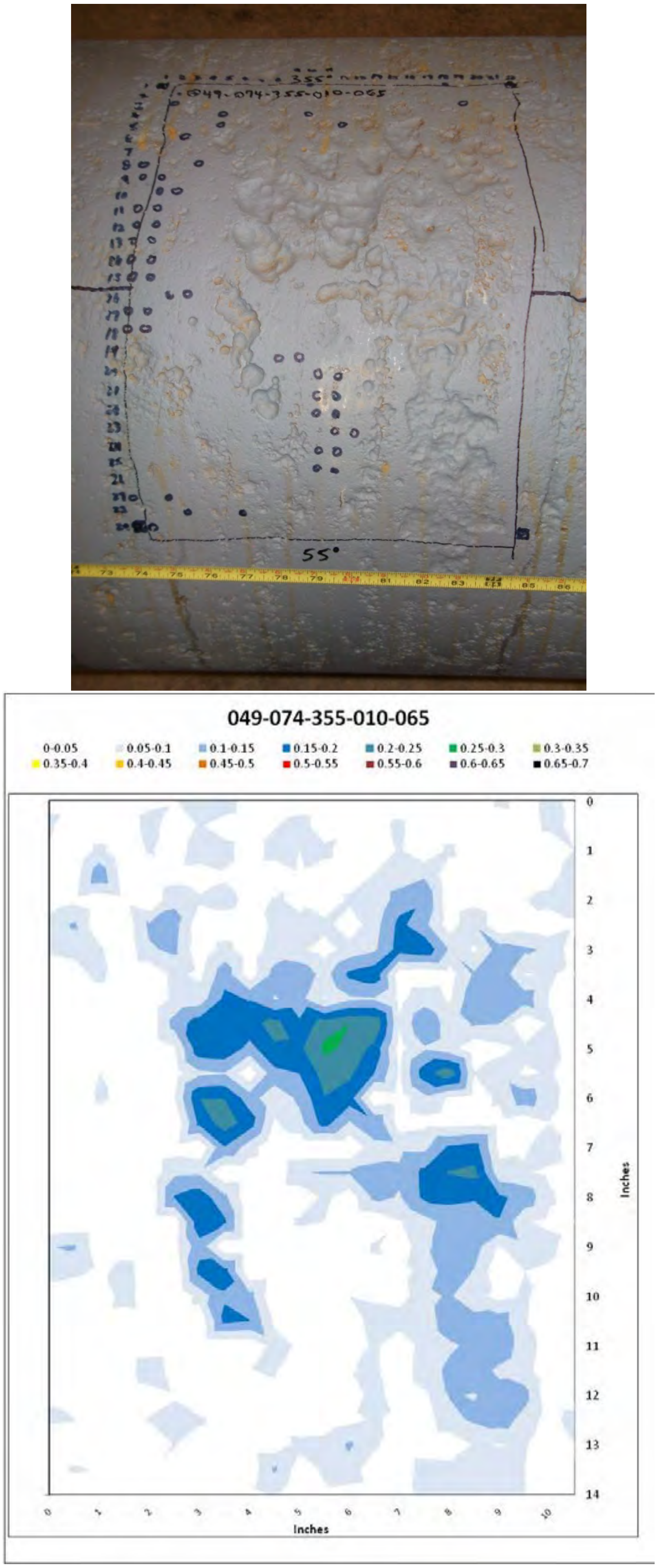


Figure A-49(4). Pipe 49, area 049-074-355-010-065

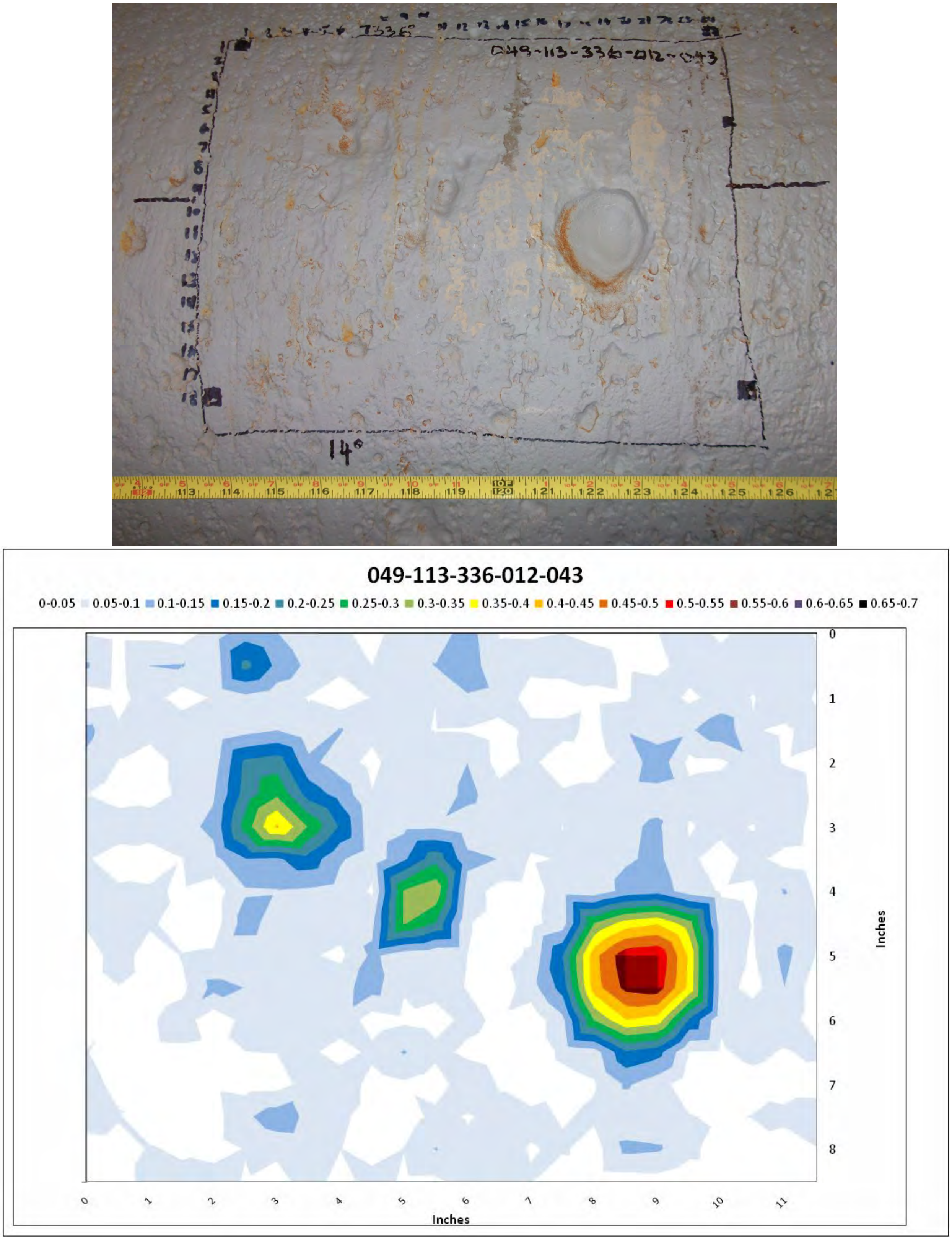


Figure A-49(5). Pipe 49, area 049-113-336-012-043

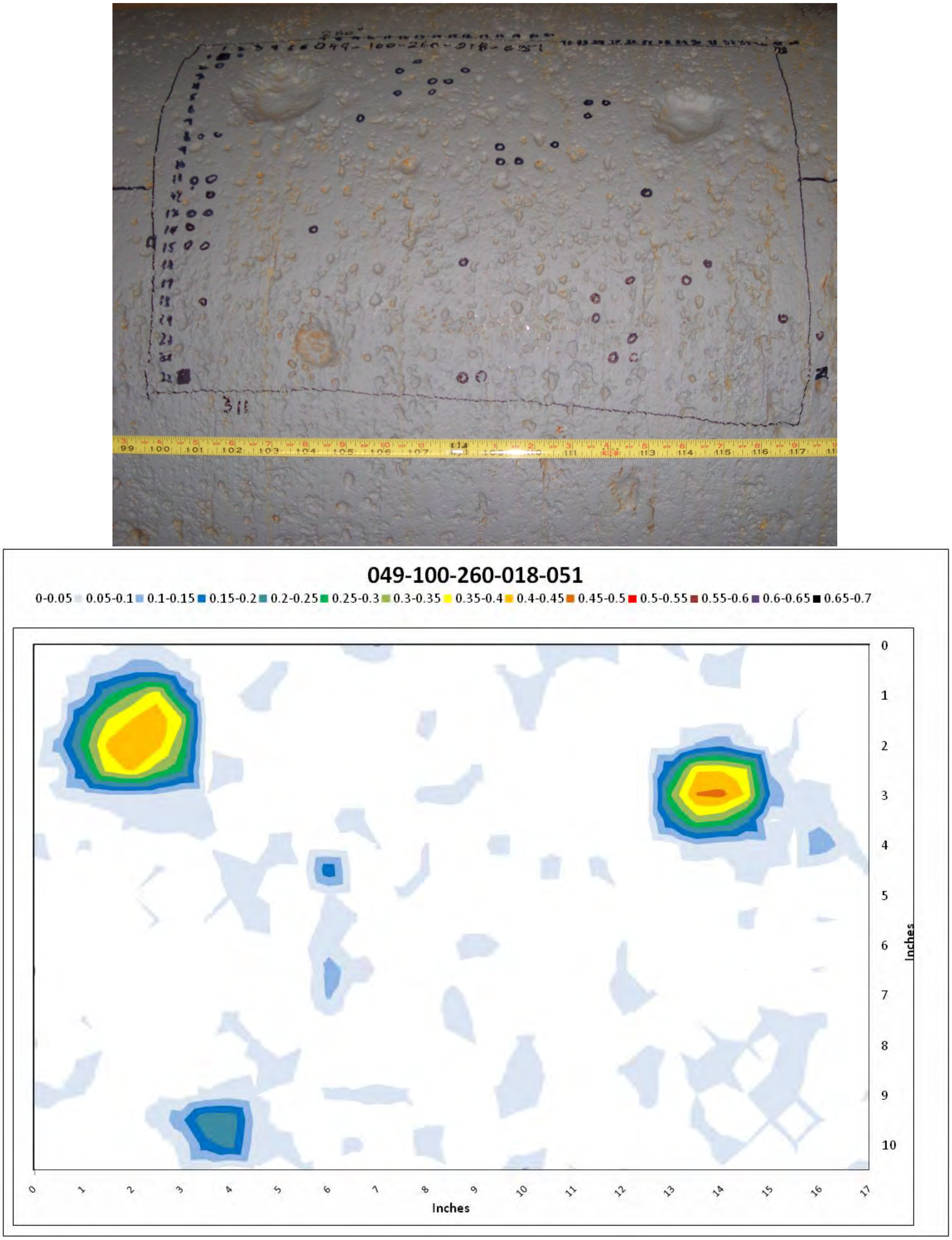


Figure A-49(6). Pipe 49, area 049-100-260-018-051

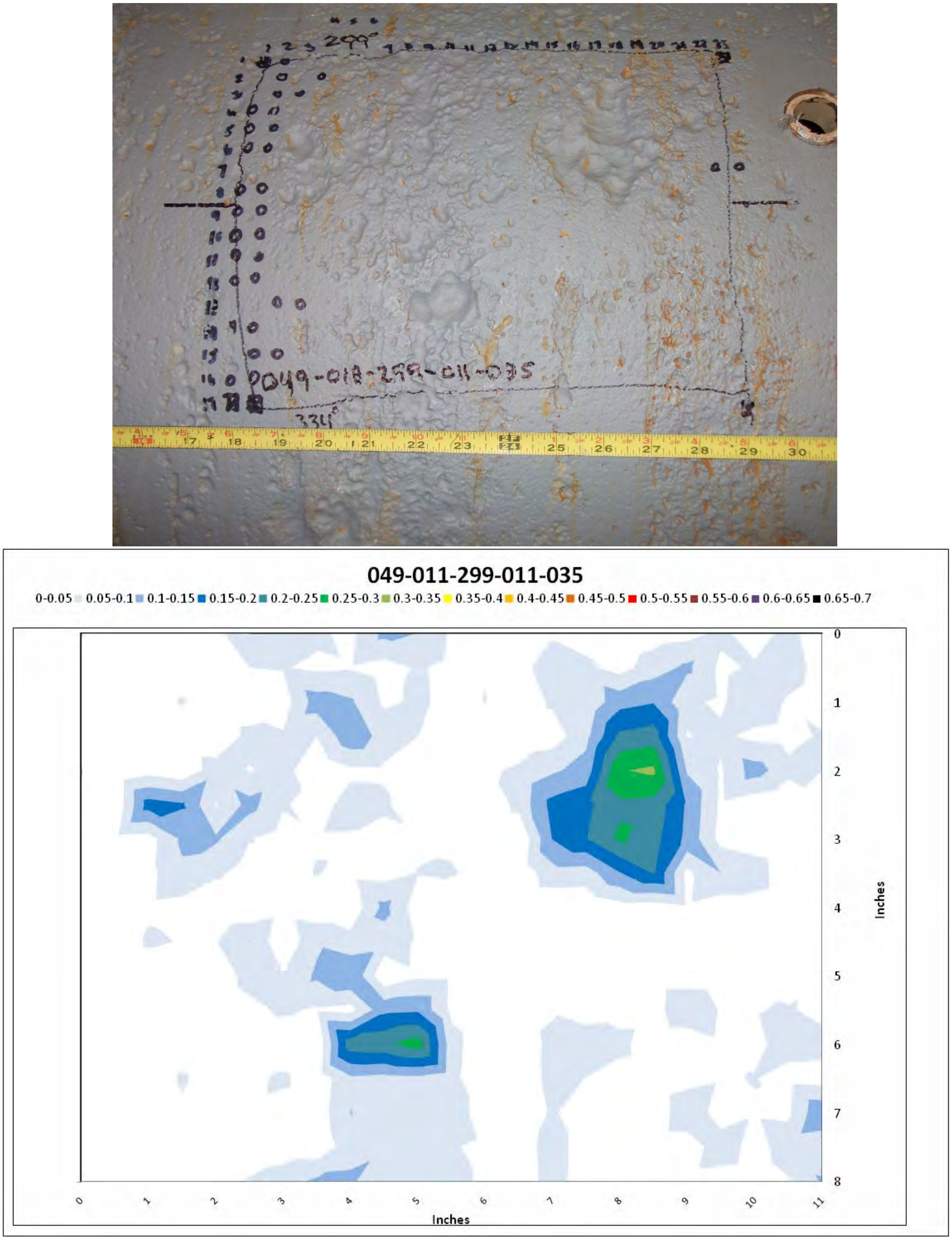


Figure A-49(7). Pipe 49, area049-011-299-011-035

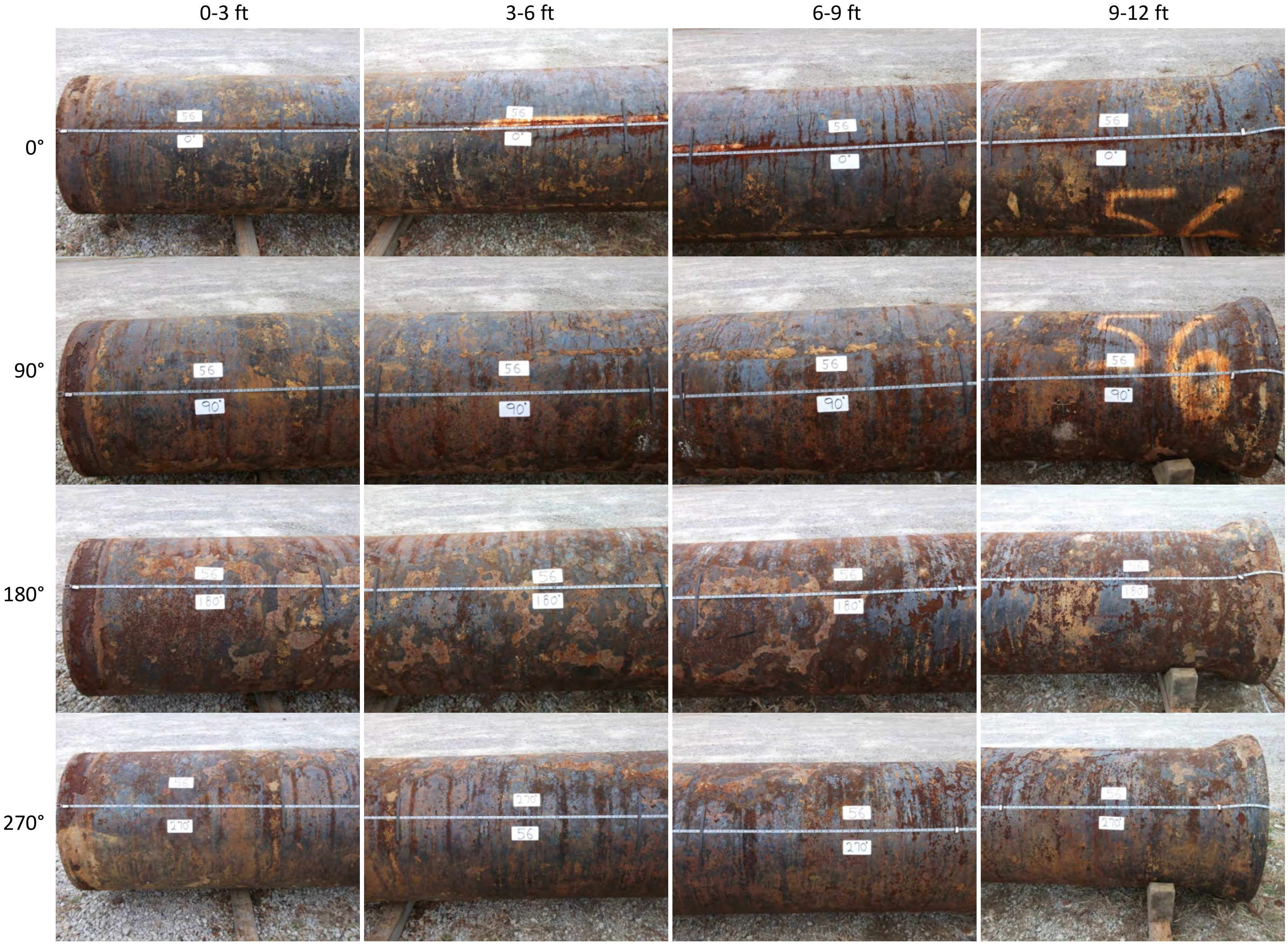


Figure A-56(1). Pipe 56 as Removed from Site

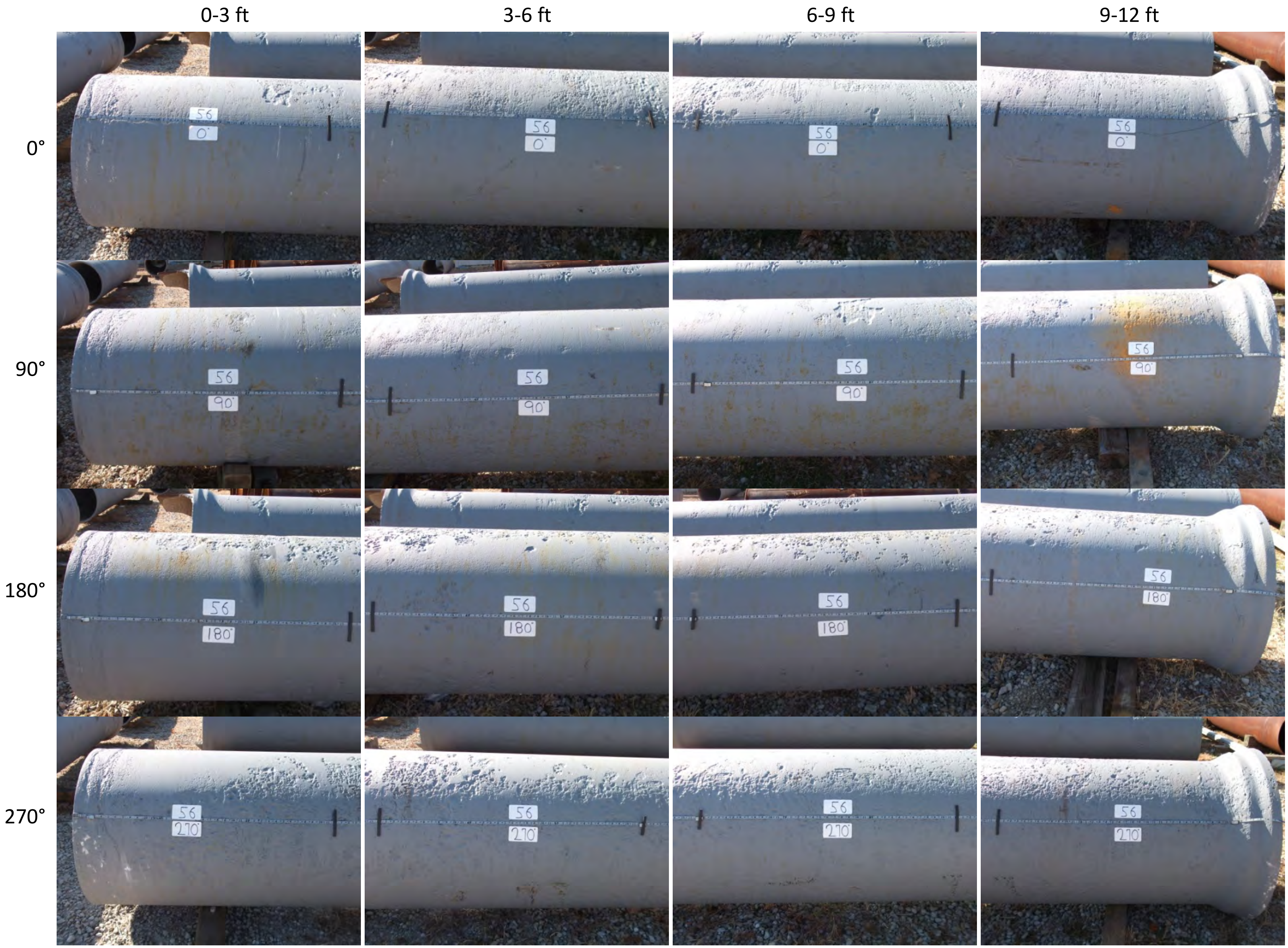


**Figure A-56(2). Pipe 56 after Sandblasting**

Table A-56(1). Wall Thickness of Cast Iron at Spigot with Caliper

| | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| Pipe Number | x° | 130 | 155° | 180° |
| 56 | x | 0.802 | 0.794 | 0.795 |

Table A-56(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)

| | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| Pipe Number | Caliper | UT | | | UT | | | UT | | |
| 56 | 0.804 | 0.781 | 0.772 | 0.759 | 0.797 | 0.789 | 0.792 | 0.762 | 0.757 | 0.749 |
| | 0.813 | 0.759 | 0.762 | 0.781 | 0.796 | 0.798 | 0.802 | 0.750 | 0.741 | 0.740 |
| | 0.816 | 0.773 | 0.769 | 0.768 | 0.800 | 0.795 | 0.794 | 0.780 | 0.747 | 0.762 |
| **Average** | 0.811 | 0.769 | | | 0.796 | | | 0.754 | | |
| **Standard Deviation** | 0.006 | 0.008 | | | 0.004 | | | 0.013 | | |
| **Minimum** | 0.804 | 0.759 | | | 0.789 | | | 0.740 | | |
| **Maximum** | 0.816 | 0.781 | | | 0.802 | | | 0.780 | | |
| **Repeat Center Cell** | - | 0.776 | | | 0.798 | | | 0.760 | | |

Table A-56(3). Outer Diameter Measurement Using a pi Tape

| | Outer Diameter | | |
|---|---|---|---|
| Pipe Number | Spigot | Center | Bell |
| 56 | 25.823 | 25.785 | 25.810 |

Table A-56(4). Wall Thickness of Cement Liner at Spigot with Caliper

| Measurement (Inches) | x° | 130 | 155° | 180° |
|---|---|---|---|---|
| **Cast Iron** | x | 0.802 | 0.794 | 0.795 |
| **Cast Iron & Cement Liner** | x | 0.995 | 0.998 | 0.990 |
| **Cement Liner** | x | 0.193 | 0.204 | 0.195 |

**Table A-56(5). Scanned Pipe 56 Summary Table**

| Defect Area | Total Volume Loss (in$^3$) | Dist From Spigot (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| H11 | -2.0 | 24.0 | 0.1870 | 24% | 0.5820 | 76% | 22 | 0:44 |
| | | 28.0 | 0.1677 | 22% | 0.6013 | 78% | 65 | 2:09 |
| H12 | -6.4 | 28.0 | 0.2890 | 38% | 0.4800 | 62% | 98 | 3:15 |
| | | 30.5 | 0.2291 | 30% | 0.5399 | 70% | 93 | 3:06 |
| | | 39.0 | 0.2291 | 30% | 0.5399 | 70% | 127 | 4:13 |
| | | 32.5 | 0.2043 | 27% | 0.5647 | 73% | 120 | 3:59 |
| H13 | 8.9 | 13.5 | 0.3039 | 40% | 0.4651 | 60% | 253 | 8:26 |
| | | 22.0 | 0.3012 | 39% | 0.4678 | 61% | 244 | 8:08 |
| | | 37.5 | 0.2106 | 27% | 0.5584 | 73% | 255 | 8:30 |
| | | 27.0 | 0.2012 | 26% | 0.5678 | 74% | 253 | 8:26 |
| H14 | -5.1 | 14.0 | 0.2028 | 26% | 0.5662 | 74% | 273 | 9:06 |
| | | 19.5 | 0.1957 | 25% | 0.5733 | 75% | 275 | 9:10 |
| | | 39.0 | 0.2028 | 26% | 0.5662 | 74% | 291 | 9:42 |
| H21 | -1.5 | 50.0 | 0.2130 | 27% | 0.5830 | 73% | 89 | 2:57 |
| | | 46.0 | 0.1890 | 24% | 0.6070 | 76% | 51 | 1:42 |
| | | 72.0 | 0.1587 | 20% | 0.6373 | 80% | 0 | 0:00 |
| H22 | 20.6 | 39.5 | 0.2291 | 29% | 0.5669 | 71% | 127 | 4:13 |
| | | 41.5 | 0.2272 | 29% | 0.5688 | 71% | 127 | 4:13 |
| | | 56.0 | 0.2248 | 28% | 0.5712 | 72% | 129 | 4:17 |
| | | 58.5 | 0.2217 | 28% | 0.5743 | 72% | 120 | 3:59 |
| | | 66.0 | 0.2894 | 36% | 0.5066 | 64% | 102 | 3:24 |
| H23 | 0.7 | 37.5 | 0.2106 | 26% | 0.5854 | 74% | 255 | 8:30 |
| | | 41.5 | 0.2079 | 26% | 0.5881 | 74% | 217 | 7:14 |
| | | 45.0 | 0.2799 | 35% | 0.5161 | 65% | 266 | 8:52 |
| | | 48.5 | 0.2346 | 29% | 0.5614 | 71% | 224 | 7:28 |
| H24 | 30.9 | 40.0 | 0.2354 | 30% | 0.5606 | 70% | 286 | 9:32 |
| | | 42.0 | 0.2354 | 30% | 0.5606 | 70% | 286 | 9:32 |
| | | 43.0 | 0.2299 | 29% | 0.5661 | 71% | 271 | 9:02 |
| | | 45.0 | 0.2780 | 35% | 0.5180 | 65% | 266 | 8:52 |
| | | 46.5 | 0.2193 | 28% | 0.5767 | 72% | 277 | 9:14 |
| | | 72.5 | 0.2315 | 29% | 0.5645 | 71% | 329 | 10:58 |
| | | 72.0 | 0.3043 | 38% | 0.4917 | 62% | 355 | 11:50 |
| H31 | -17.9 | 96.5 | 0.1693 | 21% | 0.6267 | 79% | 5 | 0:09 |
| H32 | 45.6 | 98.5 | 0.2465 | 31% | 0.5495 | 69% | 122 | 4:04 |
| | | 105.9 | 0.2862 | 36% | 0.5098 | 64% | 118 | 3:55 |
| | | 107.0 | 0.3126 | 39% | 0.4834 | 61% | 169 | 5:37 |
| | | 74.4 | 0.2051 | 26% | 0.5909 | 74% | 115 | 3:50 |
| | | 88.5 | 0.3398 | 43% | 0.4562 | 57% | 122 | 4:04 |

| Defect Area | Total Volume Loss ($in^3$) | Dist From Spigot (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| | | 88.0 | 0.2713 | 34% | 0.5247 | 66% | 118 | 3:55 |
| | | 92.0 | 0.2709 | 34% | 0.5251 | 66% | 118 | 3:55 |
| | | 94.0 | 0.2563 | 32% | 0.5397 | 68% | 120 | 3:59 |
| | | 95.5 | 0.2437 | 31% | 0.5523 | 69% | 133 | 4:26 |
| | | 97.4 | 0.3823 | 48% | 0.4137 | 52% | 173 | 5:46 |
| H33 | -9.9 | 97.4 | 0.2673 | 34% | 0.5287 | 66% | 178 | 5:55 |
| | | 107.0 | 0.2138 | 27% | 0.5822 | 73% | 178 | 5:55 |
| H34 | 39.9 | 72.5 | 0.2956 | 37% | 0.5004 | 63% | 355 | 11:50 |
| | | 72.5 | 0.2315 | 29% | 0.5645 | 71% | 329 | 10:58 |
| | | 66.0 | 0.2283 | 29% | 0.5677 | 71% | 309 | 10:18 |
| | | 73.0 | 0.2138 | 27% | 0.5822 | 73% | 324 | 10:48 |
| H41 | 9.5 | 133.5 | 0.2083 | 28% | 0.5457 | 72% | 76 | 2:31 |
| | | 119.0 | 0.1929 | 26% | 0.5611 | 74% | 69 | 2:17 |
| H42 | 72.0 | 107.0 | 0.3126 | 41% | 0.4414 | 59% | 169 | 5:38 |
| | | 109.0 | 0.2634 | 35% | 0.4906 | 65% | 173 | 5:46 |
| | | 111.1 | 0.3386 | 45% | 0.4154 | 55% | 173 | 5:46 |
| | | 113.0 | 0.3406 | 45% | 0.4134 | 55% | 146 | 4:52 |
| | | 113.0 | 0.2508 | 33% | 0.5032 | 67% | 135 | 4:30 |
| | | 114.5 | 0.2516 | 33% | 0.5024 | 67% | 127 | 4:13 |
| | | 115.0 | 0.2504 | 33% | 0.5036 | 67% | 138 | 4:36 |
| | | 119.0 | 0.2272 | 30% | 0.5268 | 70% | 138 | 4:36 |
| | | 119.6 | 0.2264 | 30% | 0.5276 | 70% | 109 | 3:38 |
| | | 123.5 | 0.2508 | 33% | 0.5032 | 67% | 118 | 3:55 |
| | | 129.0 | 0.2709 | 36% | 0.4831 | 64% | 131 | 4:22 |
| | | 126.0 | 0.2984 | 40% | 0.4556 | 60% | 164 | 5:28 |
| | | 129.6 | 0.2453 | 33% | 0.5087 | 67% | 146 | 4:52 |
| | | 132.0 | 0.2854 | 38% | 0.4686 | 62% | 122 | 4:04 |
| | | 132.6 | 0.2366 | 31% | 0.5174 | 69% | 113 | 3:46 |
| H43 | 21.0 | 125.0 | 0.2382 | 32% | 0.5158 | 68% | 224 | 7:28 |
| | | 107.0 | 0.2134 | 28% | 0.5406 | 72% | 178 | 5:56 |
| | | 133.5 | 0.1980 | 26% | 0.5560 | 74% | 257 | 8:34 |
| H44 | 46.1 | 117.5 | 0.2378 | 32% | 0.5162 | 68% | 320 | 10:40 |
| | | 112.6 | 0.2343 | 31% | 0.5197 | 69% | 320 | 10:40 |
| | | 114.1 | 0.2354 | 31% | 0.5186 | 69% | 309 | 10:18 |
| | | 120.5 | 0.2638 | 35% | 0.4902 | 65% | 318 | 10:36 |
| | | 121.1 | 0.2362 | 31% | 0.5178 | 69% | 304 | 10:08 |

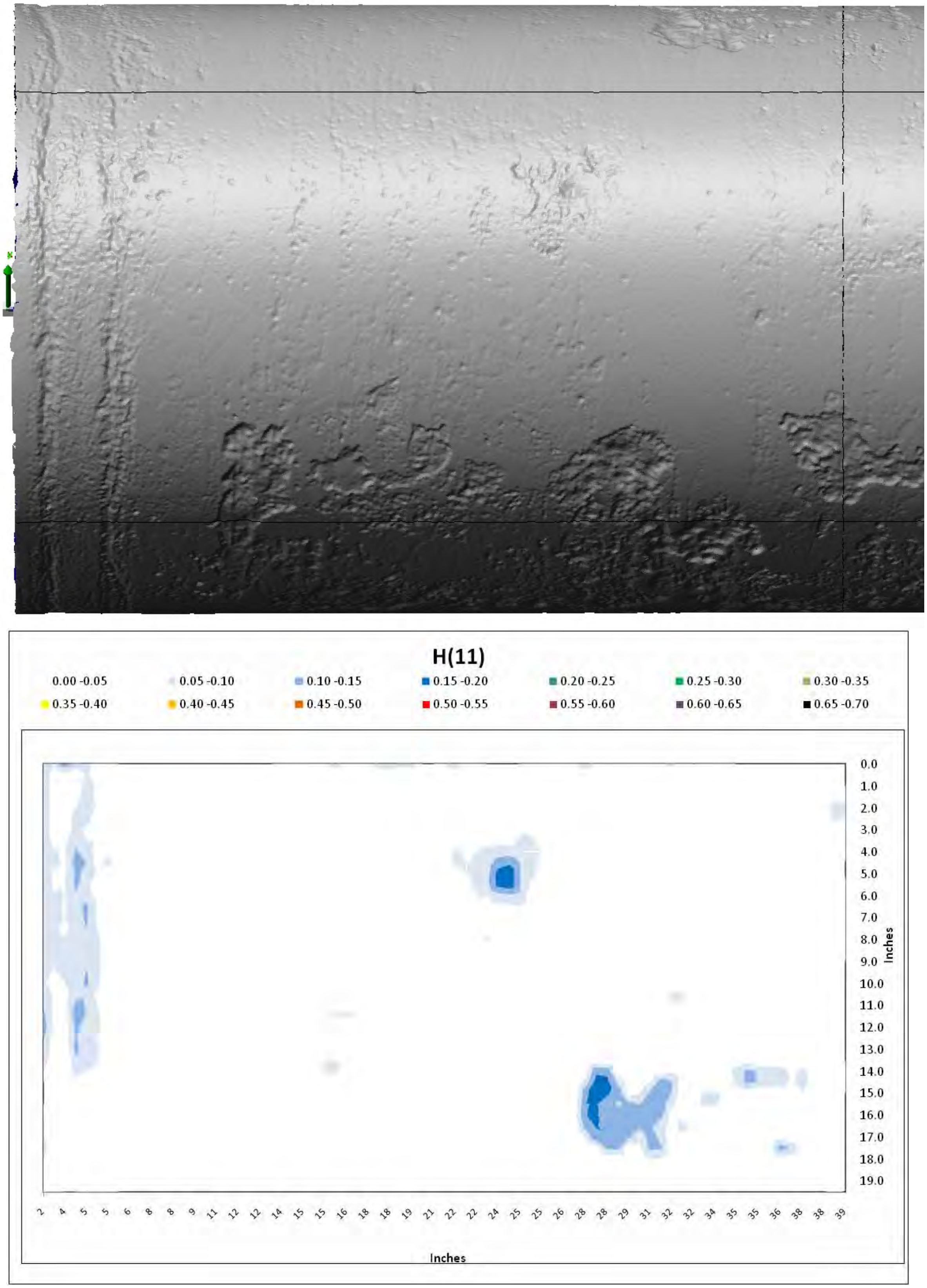


**Figure A-56(1). Pipe from 0-3 feet and 0-90 degrees**

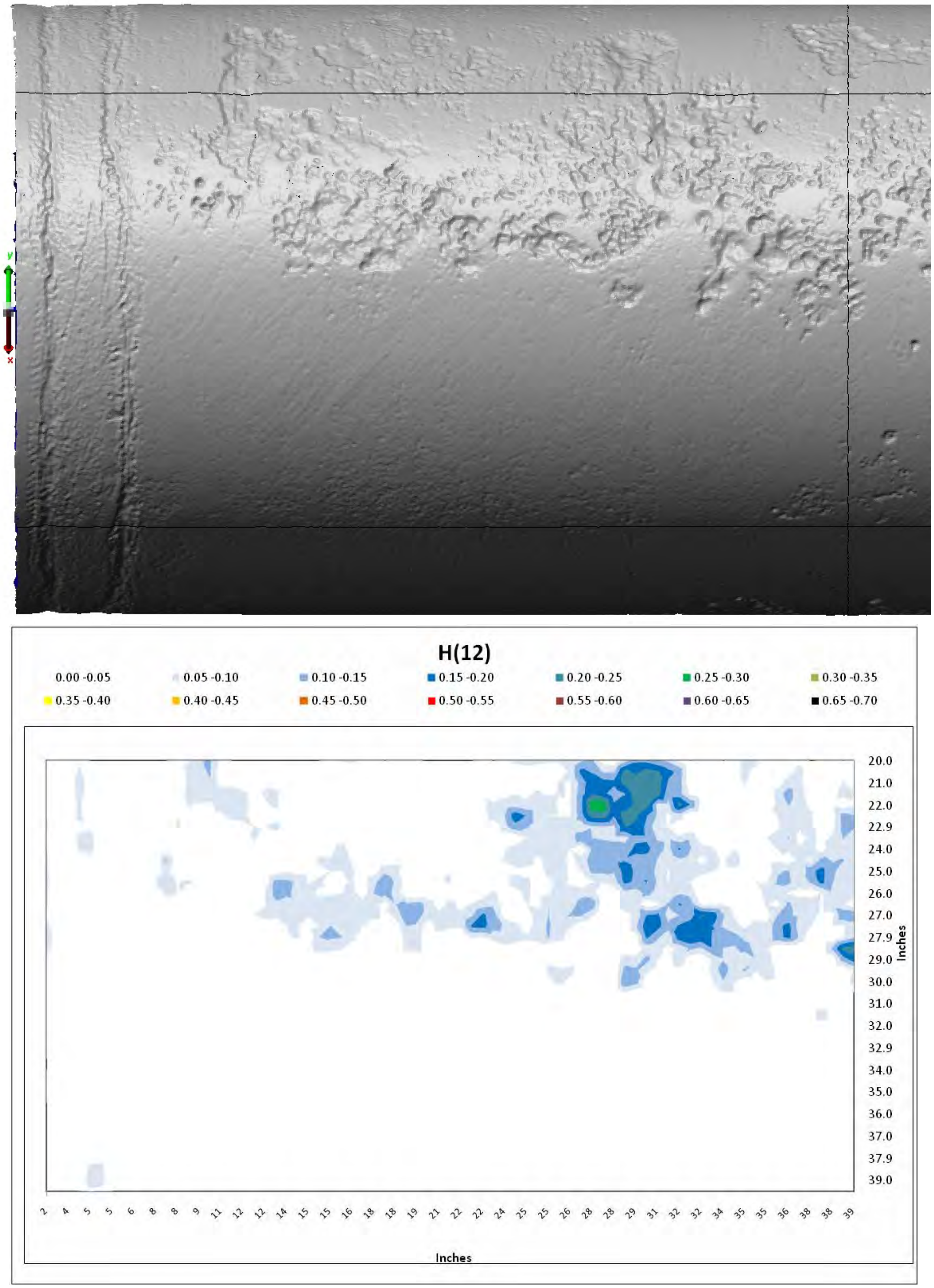


Figure A-56(2). Pipe from 0-3 feet and 90-180 degrees

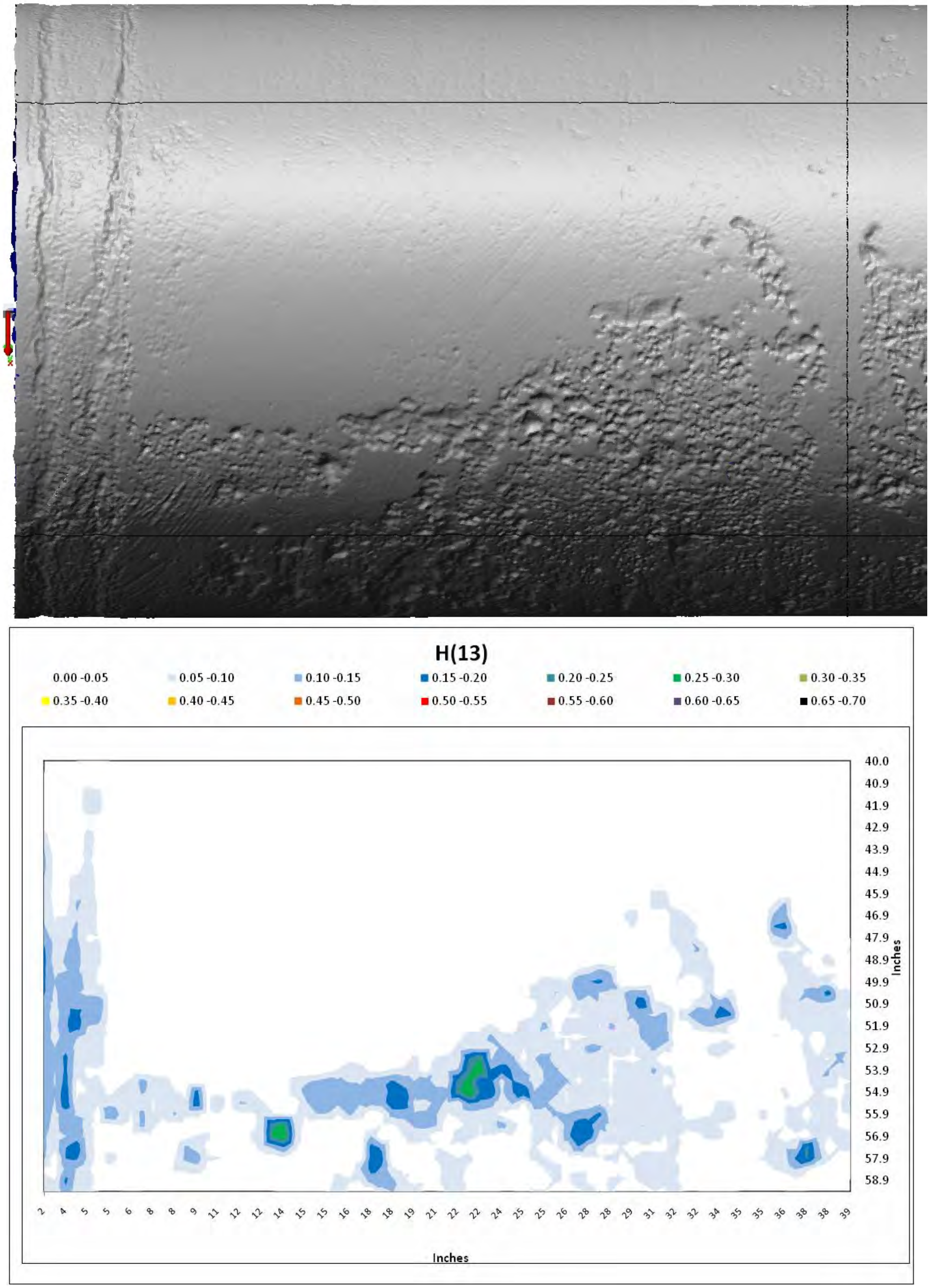


Figure A-56(3). Pipe from 0-3 feet and 180-270 degrees

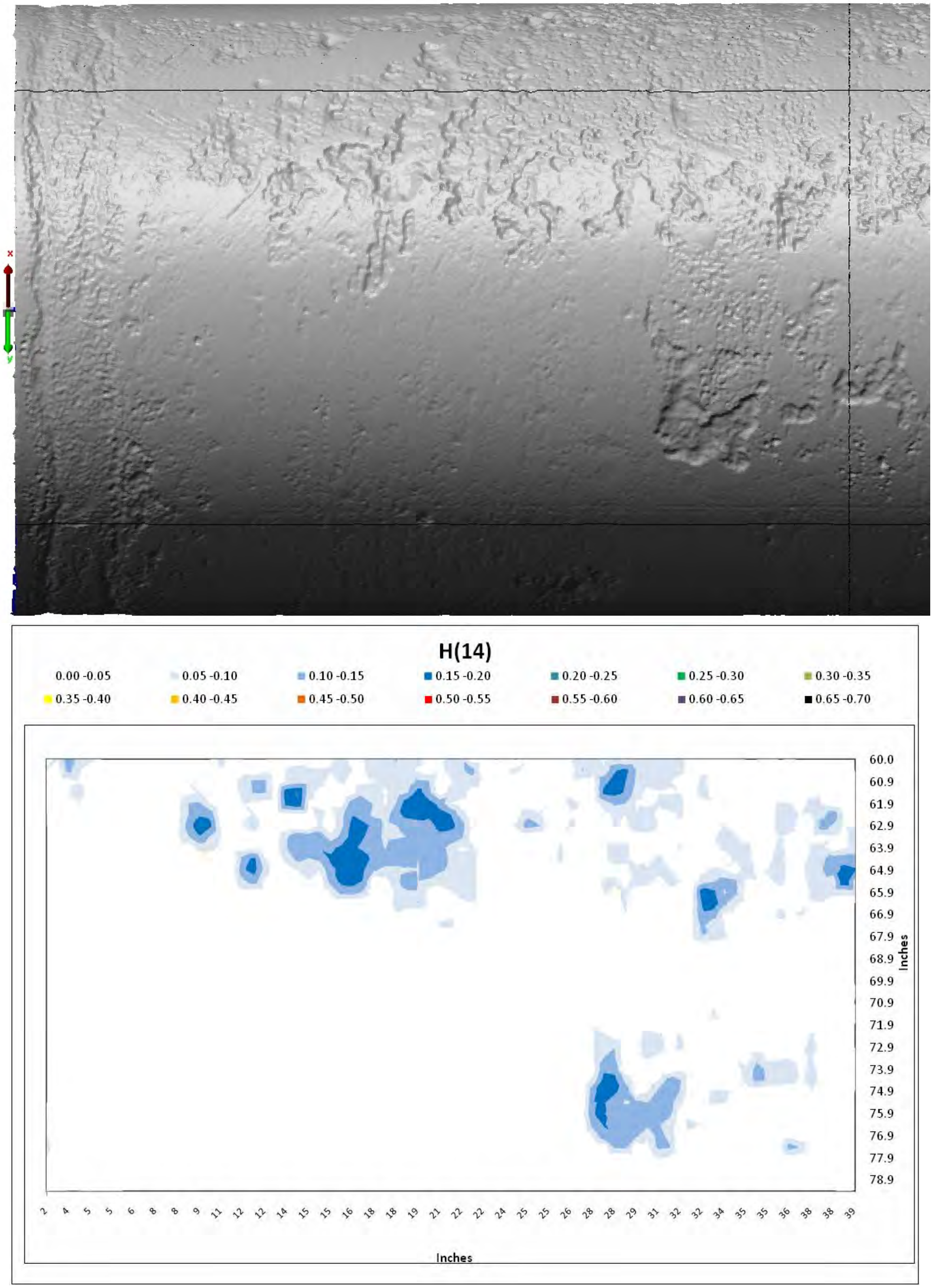


Figure A-56(4). Pipe from 0-3 feet and 270-300 degrees

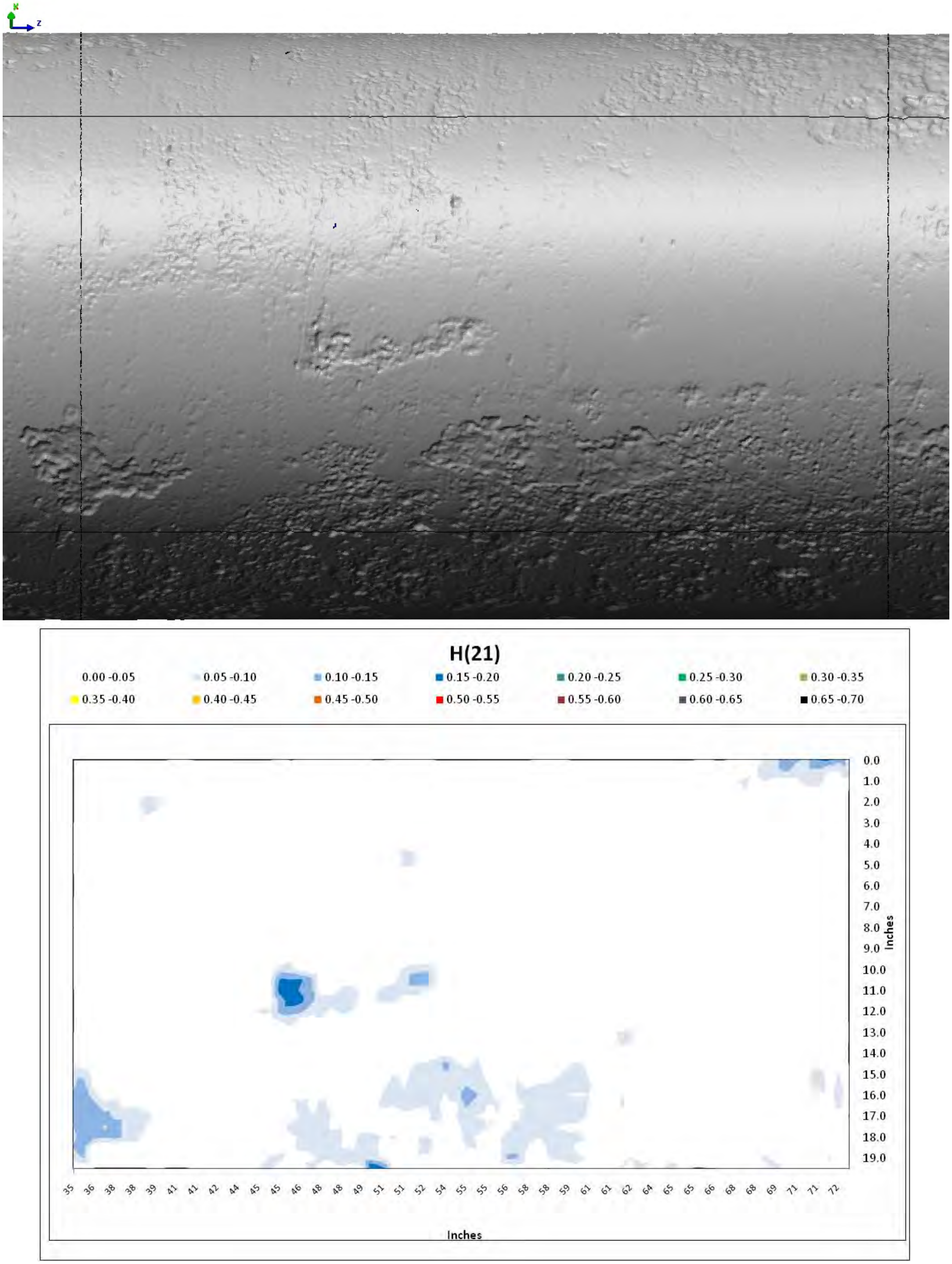


Figure A-56(5). Pipe 3-6 feet and 0-90 degrees

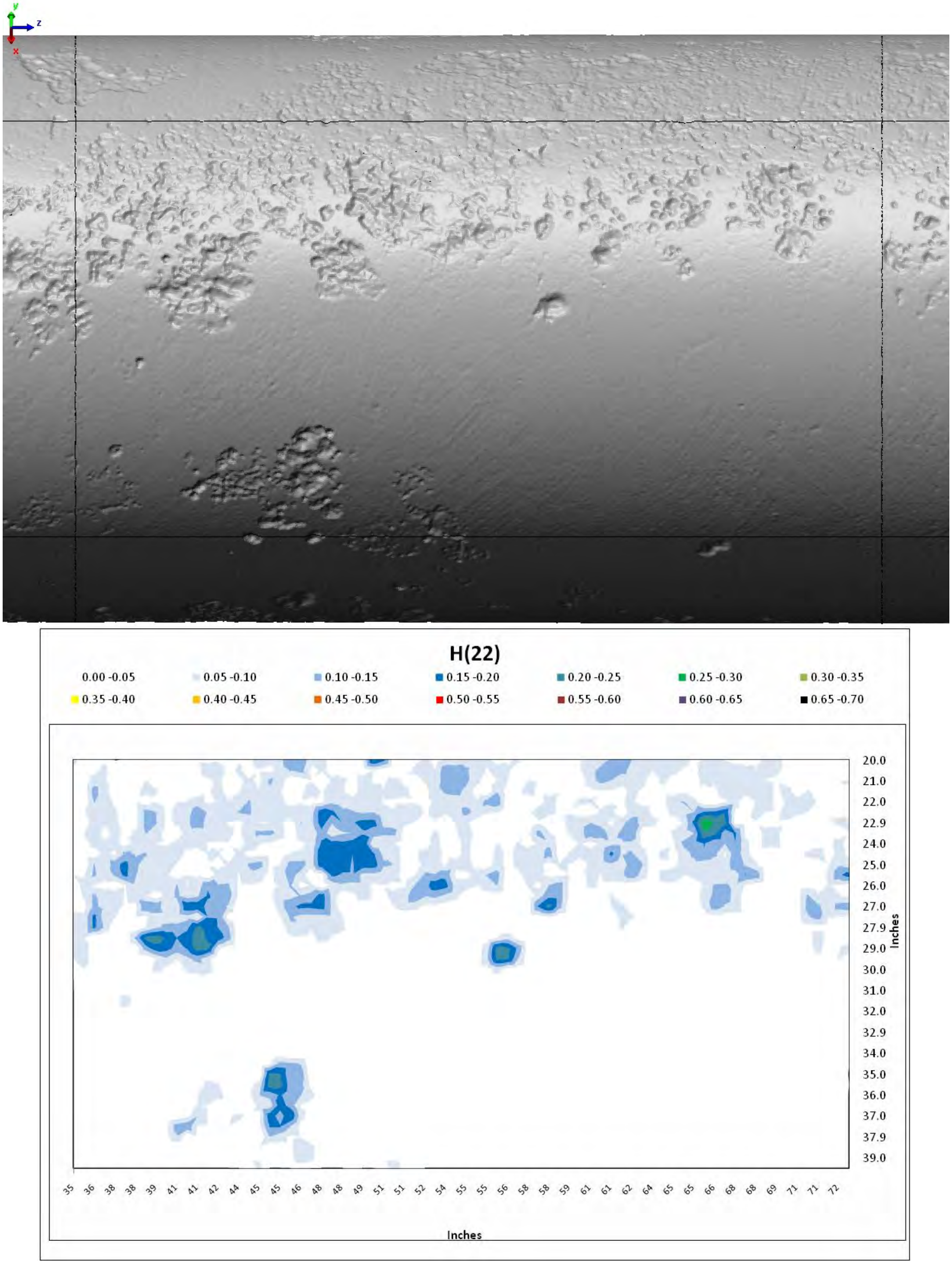


**Figure A-56(6). Pipe from 3-6 feet and 90-180 degrees**

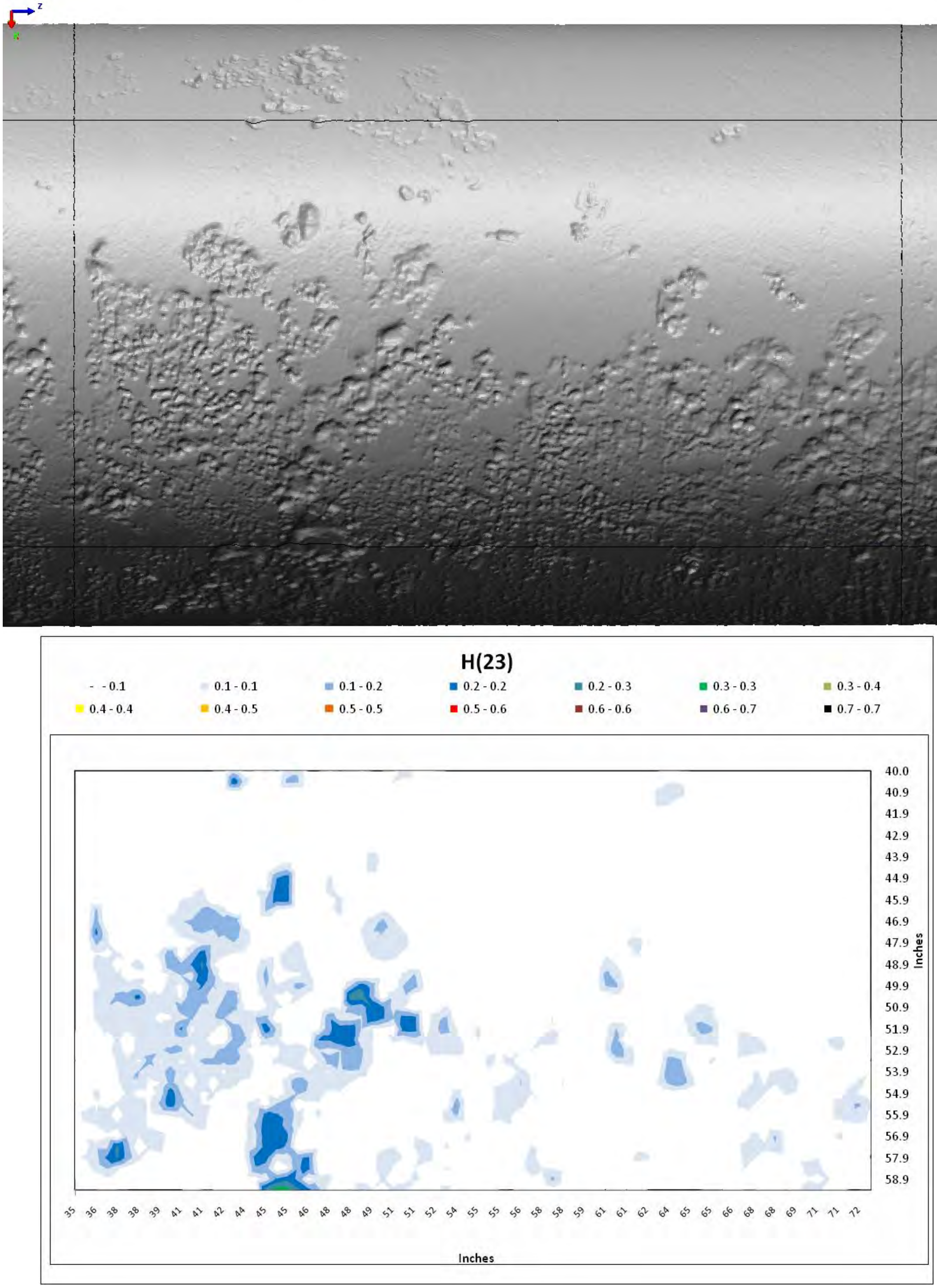


Figure A-56(7). Pipe from 3-6 feet to 180-270 degrees

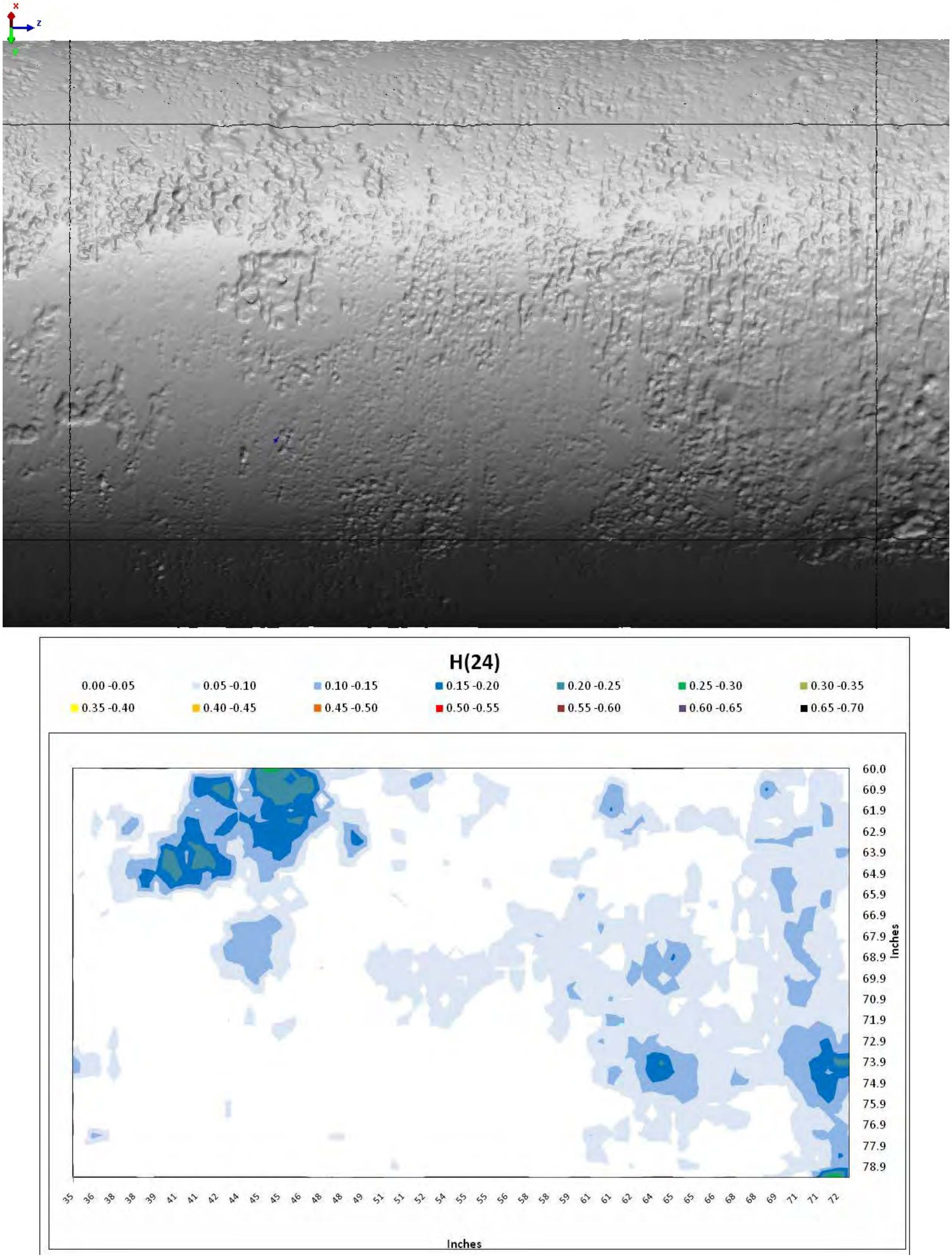


**Figure A-56(8). Pipe from 3-6 feet and 270-300 degrees**

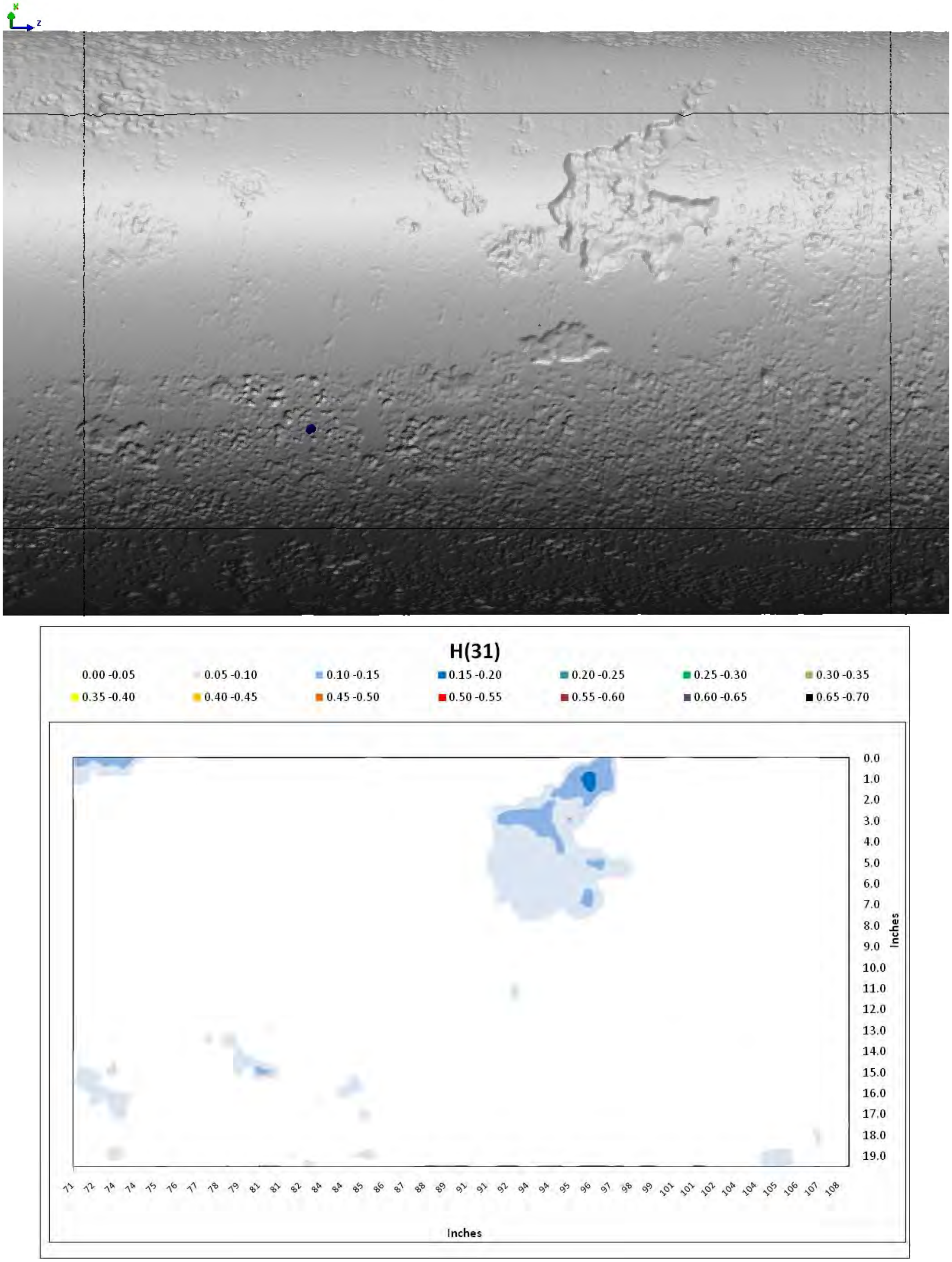


**Figure A-56(9). Pipe from 6-9 feet and 0-90 degrees**

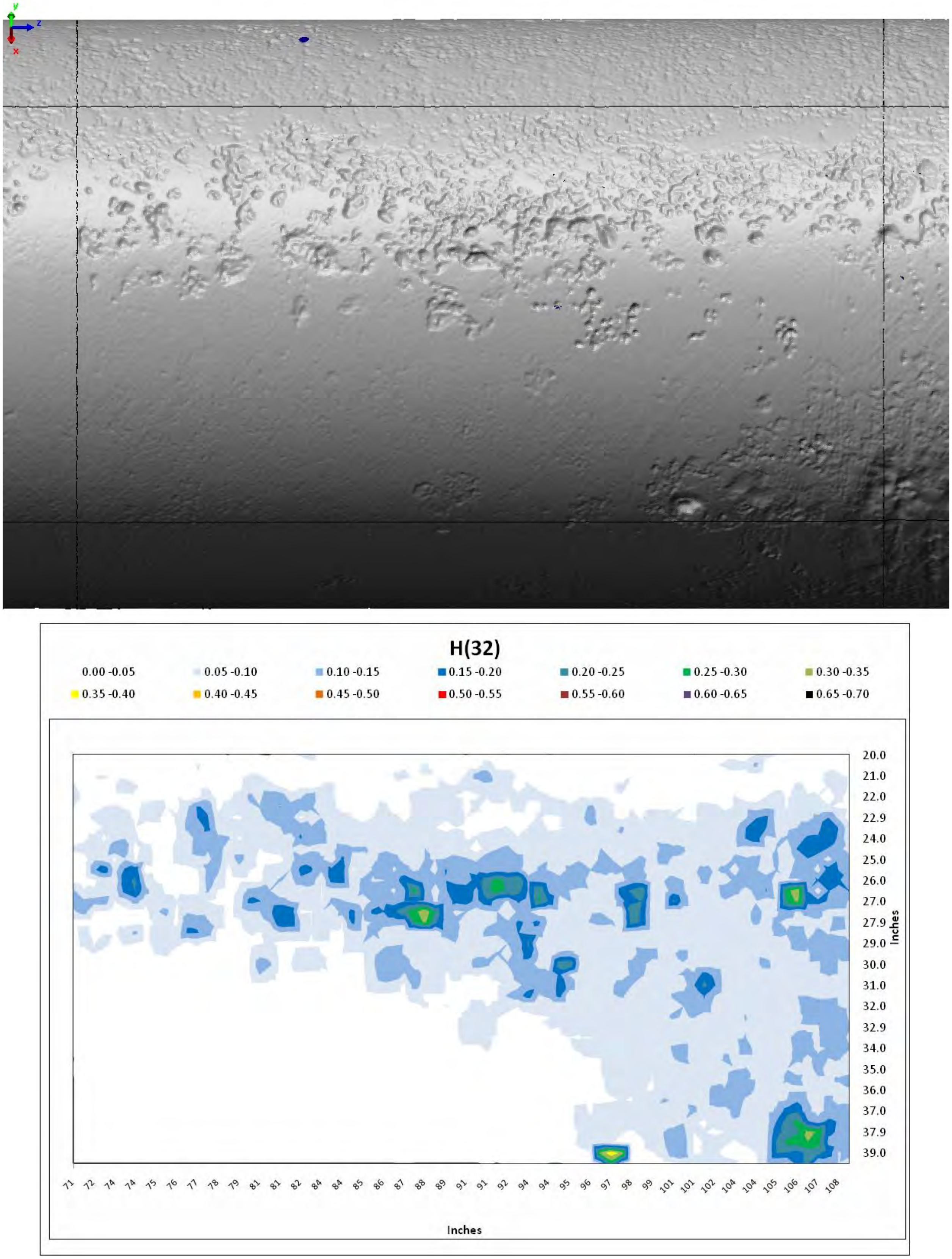


Figure A-56(10). Pipe from 6-9 feet and 90-180 degrees

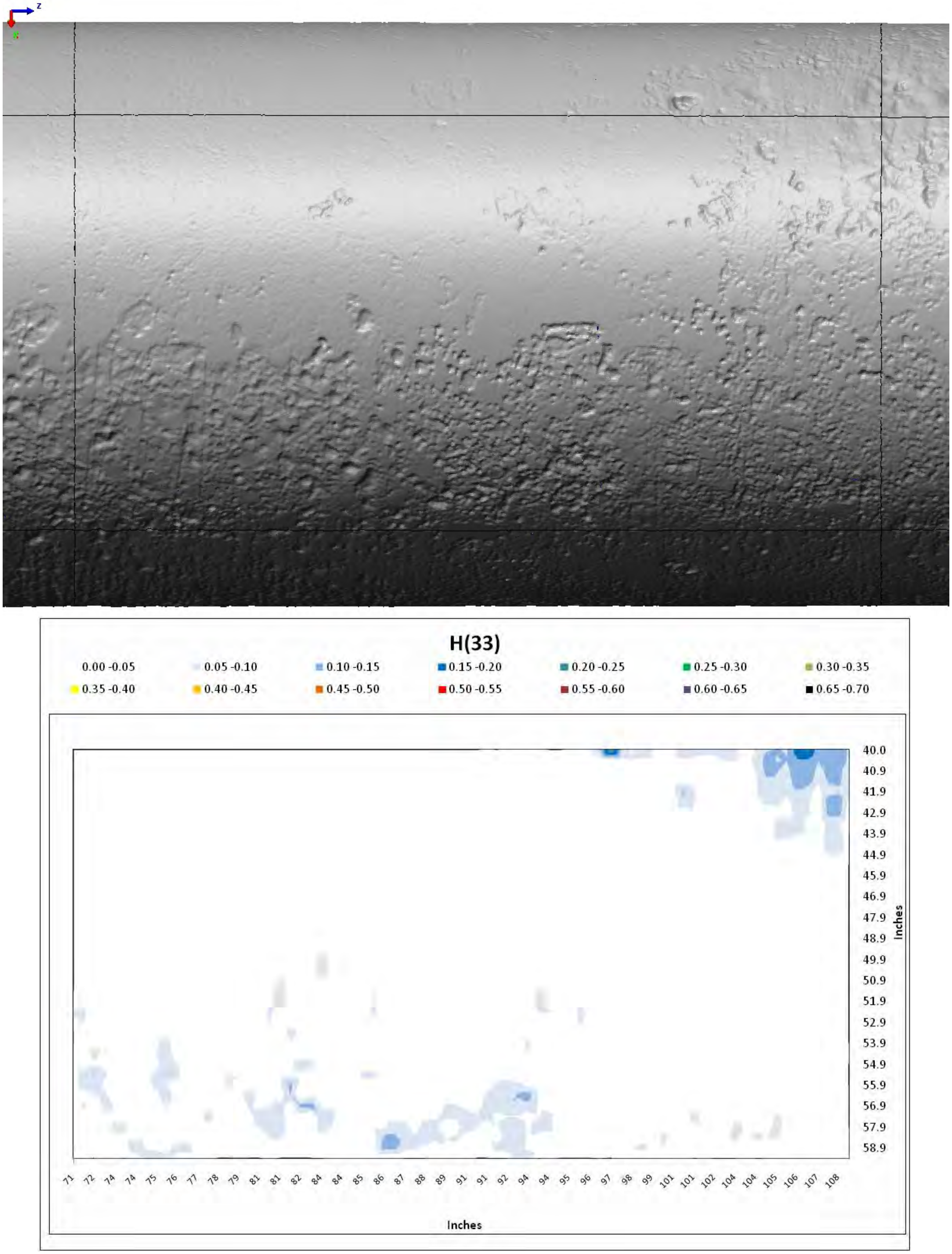


Figure A-56(11). Pipe from 6-9 feet and 180-270 degrees

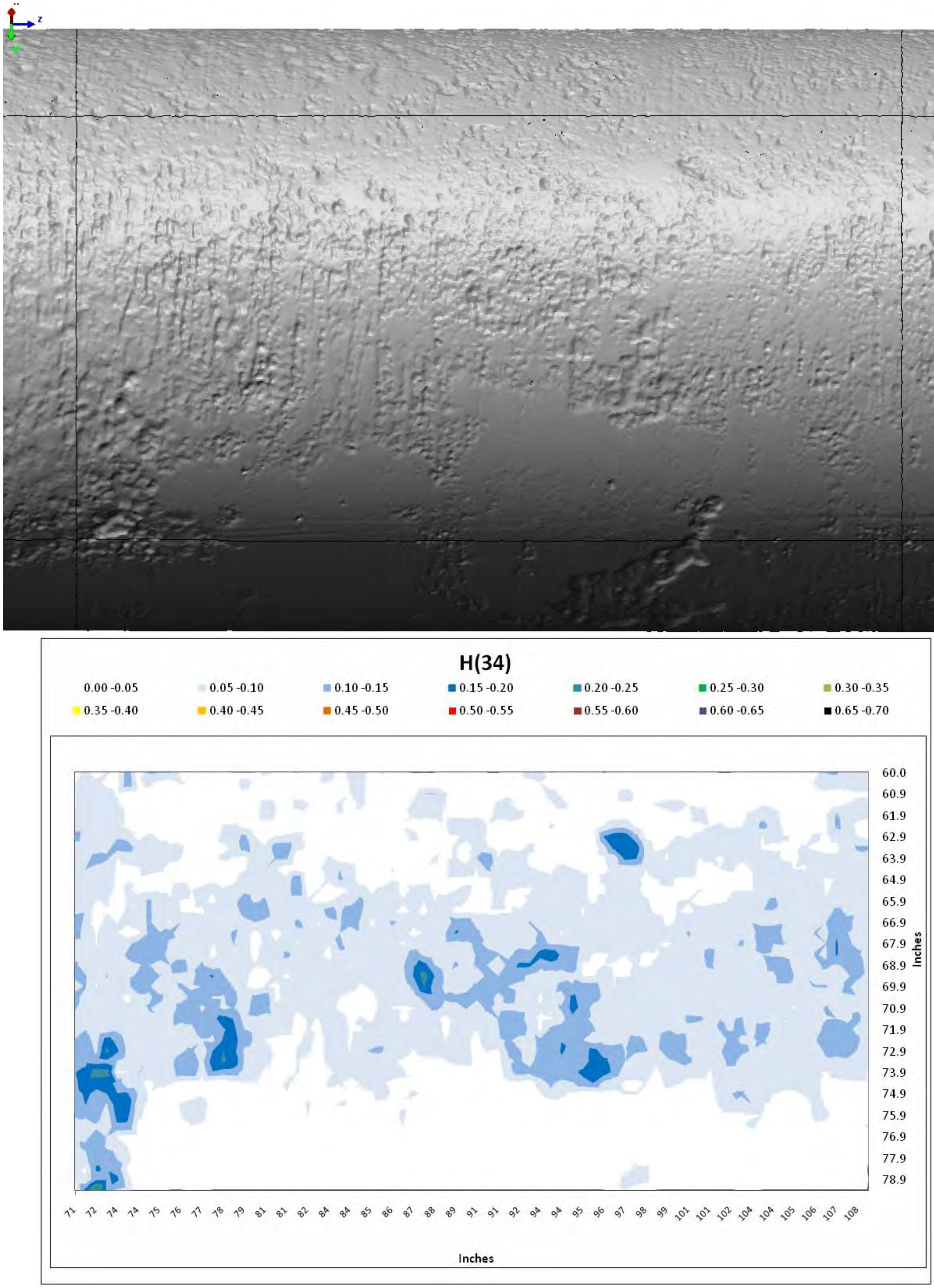


Figure A-56(12). Pipe from 6-9 feet and 270-300 degrees

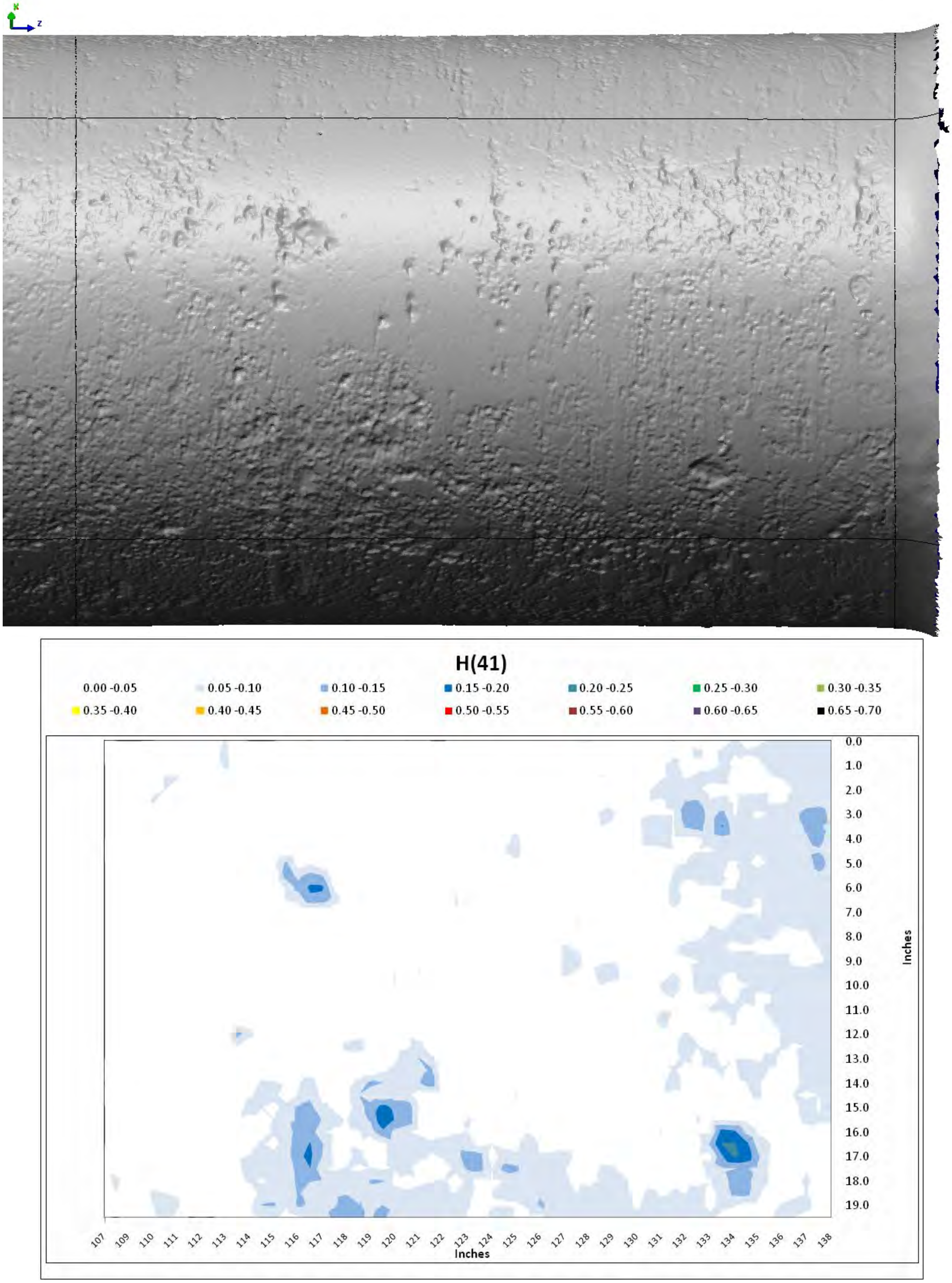


**Figure A-56(13). Pipe from 9-12 feet and 0-90 degrees**

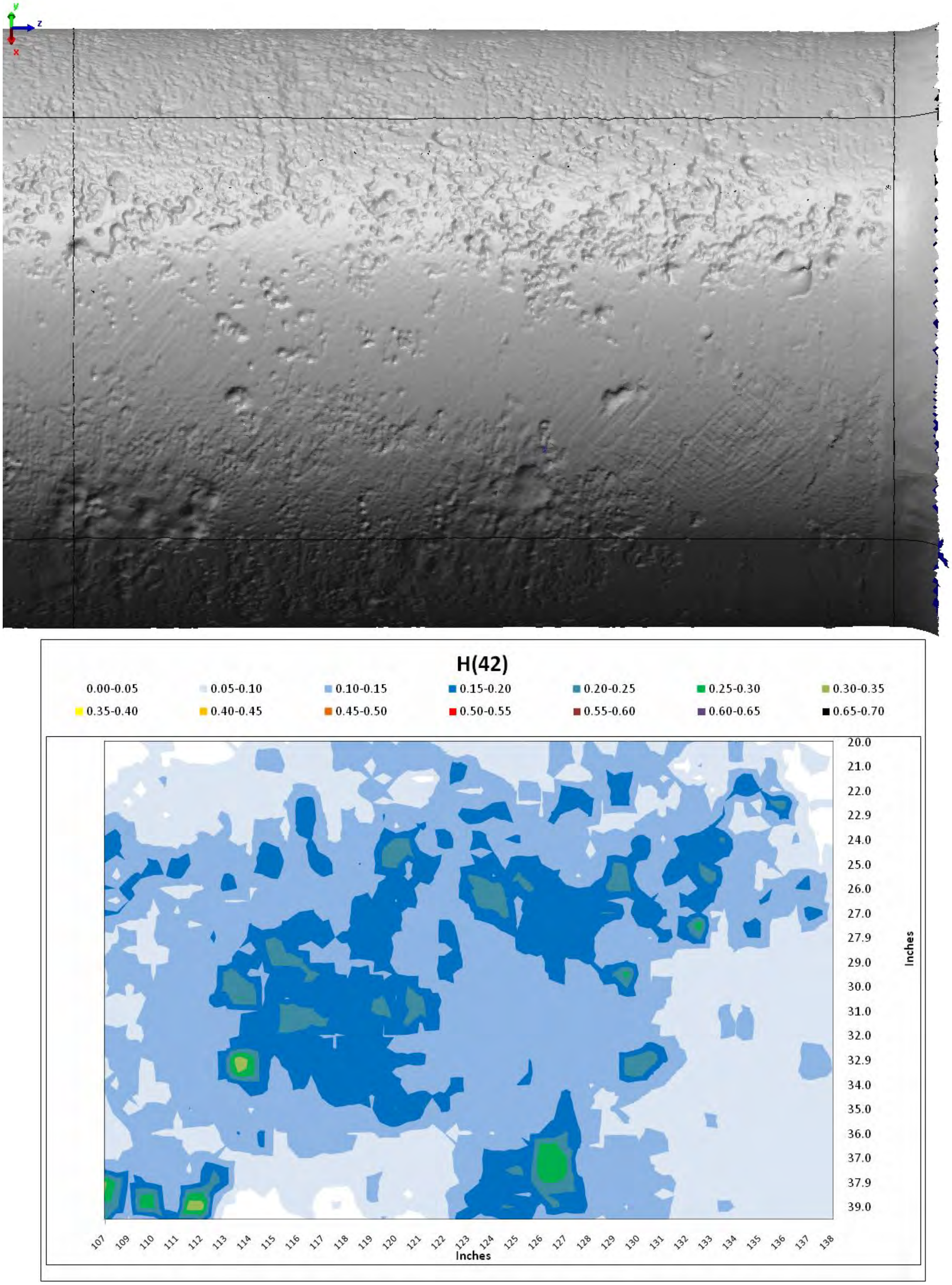


Figure A-56(14). Pipe from 9-12 feet and 90-180 degrees

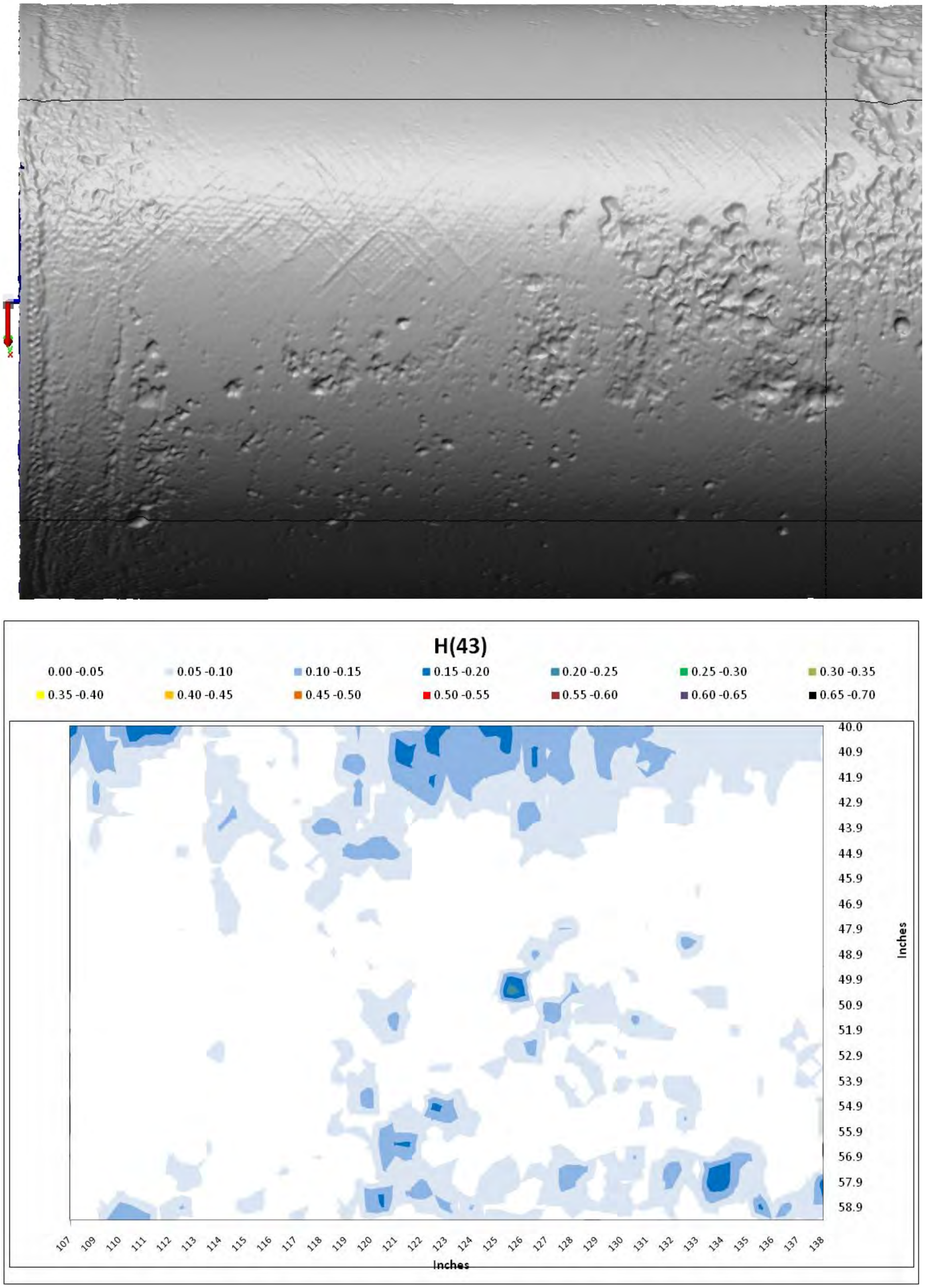


Figure A-56(15). Pipe from 9-12 feet and 180-270 degrees

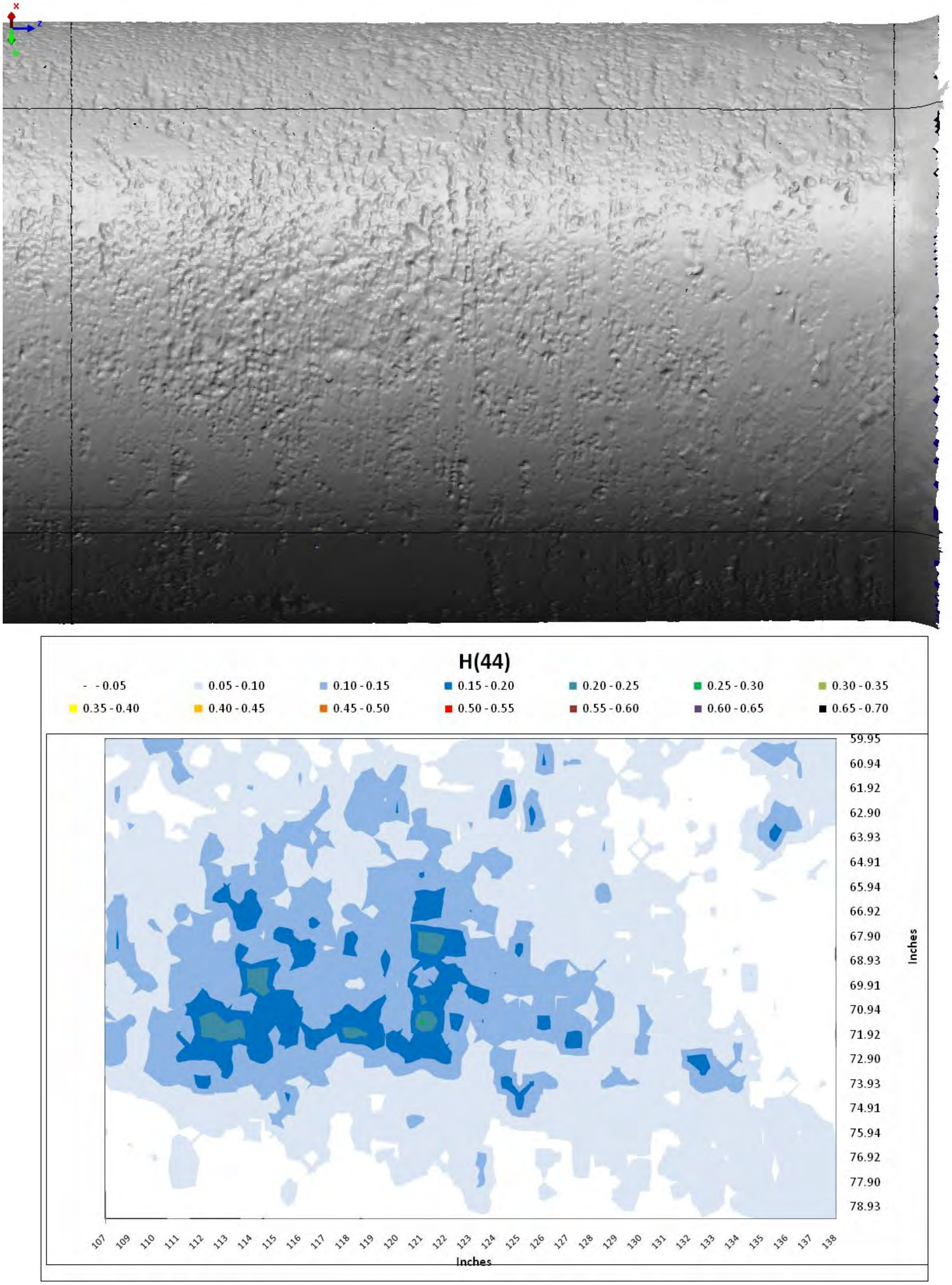


Figure A-56(16). Pipe from 9-12 feet and 270-300 degrees

Figure A-61(1). Pipe 61 as Removed from Site

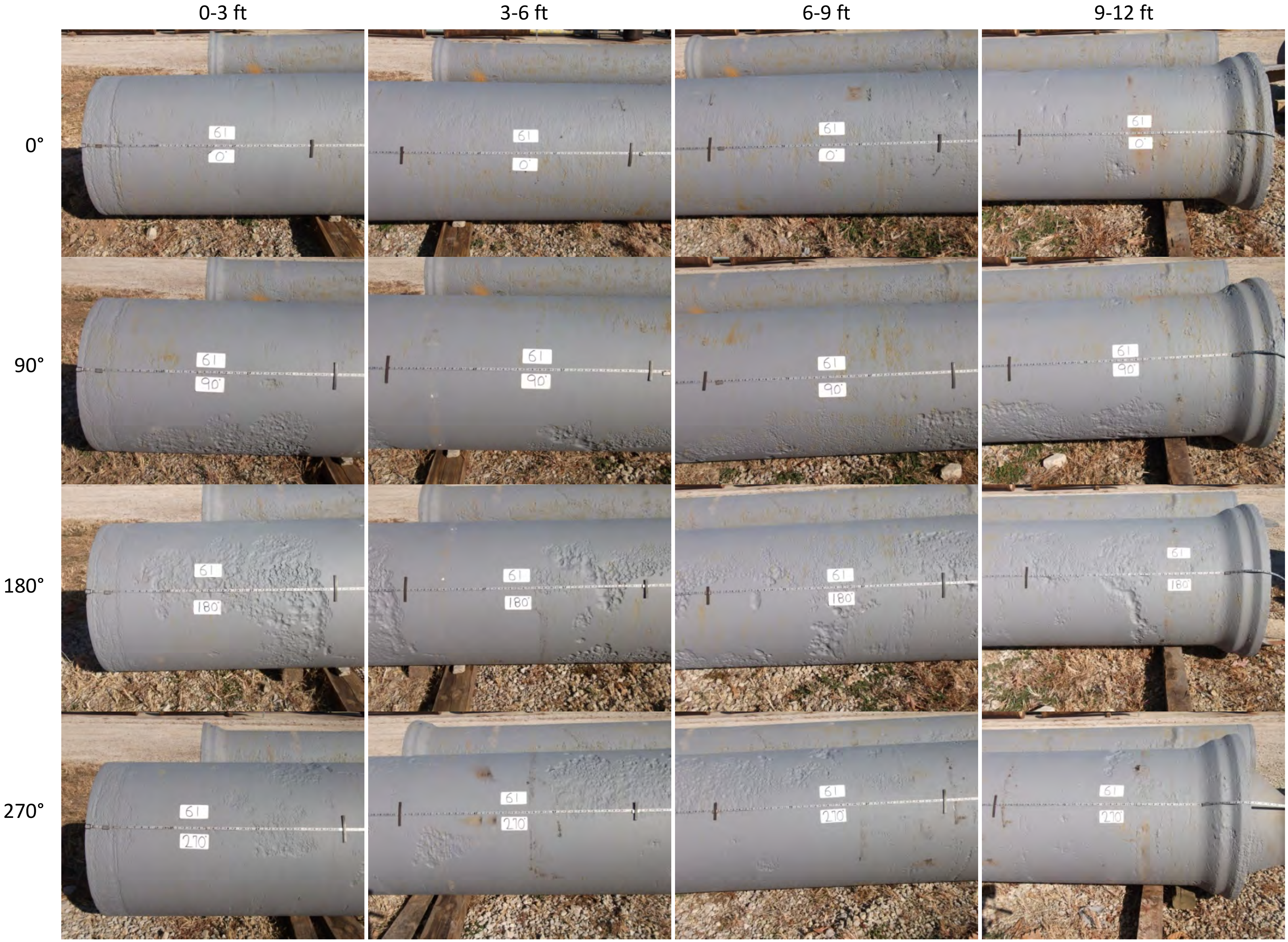


Figure A-61(2). Pipe 61 after Sandblasting

**Table A-61(1). Wall Thickness of Cast Iron at Spigot with Caliper**

| | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| Pipe Number | 0° | 90° | 205° | 280° |
| 61 | 0.803 | 0.779 | 0.784 | 0.789 |

**Table A-61(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)**

| | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| Pipe Number | Caliper | UT | | | UT | | | UT | | |
| 61 | 0.773 | 0.794 | 0.765 | 0.773 | 0.813 | 0.798 | 0.835 | 0.781 | 0.792 | 0.798 |
| | 0.780 | 0.777 | 0.783 | 0.768 | 0.827 | 0.821 | 0.820 | 0.780 | 0.777 | 0.773 |
| | 0.776 | 0.777 | 0.762 | 0.773 | 0.816 | 0.836 | 0.808 | 0.793 | 0.793 | 0.797 |
| **Average** | 0.776 | 0.775 | | | 0.819 | | | 0.787 | | |
| **Standard Deviation** | 0.004 | 0.010 | | | 0.012 | | | 0.009 | | |
| **Minimum** | 0.773 | 0.762 | | | 0.798 | | | 0.773 | | |
| **Maximum** | 0.780 | 0.794 | | | 0.836 | | | 0.798 | | |
| **Repeat Center Cell** | - | 0.769 | | | 0.808 | | | 0.792 | | |

**Table A-61(3). Outer Diameter Measurement Using a pi Tape**

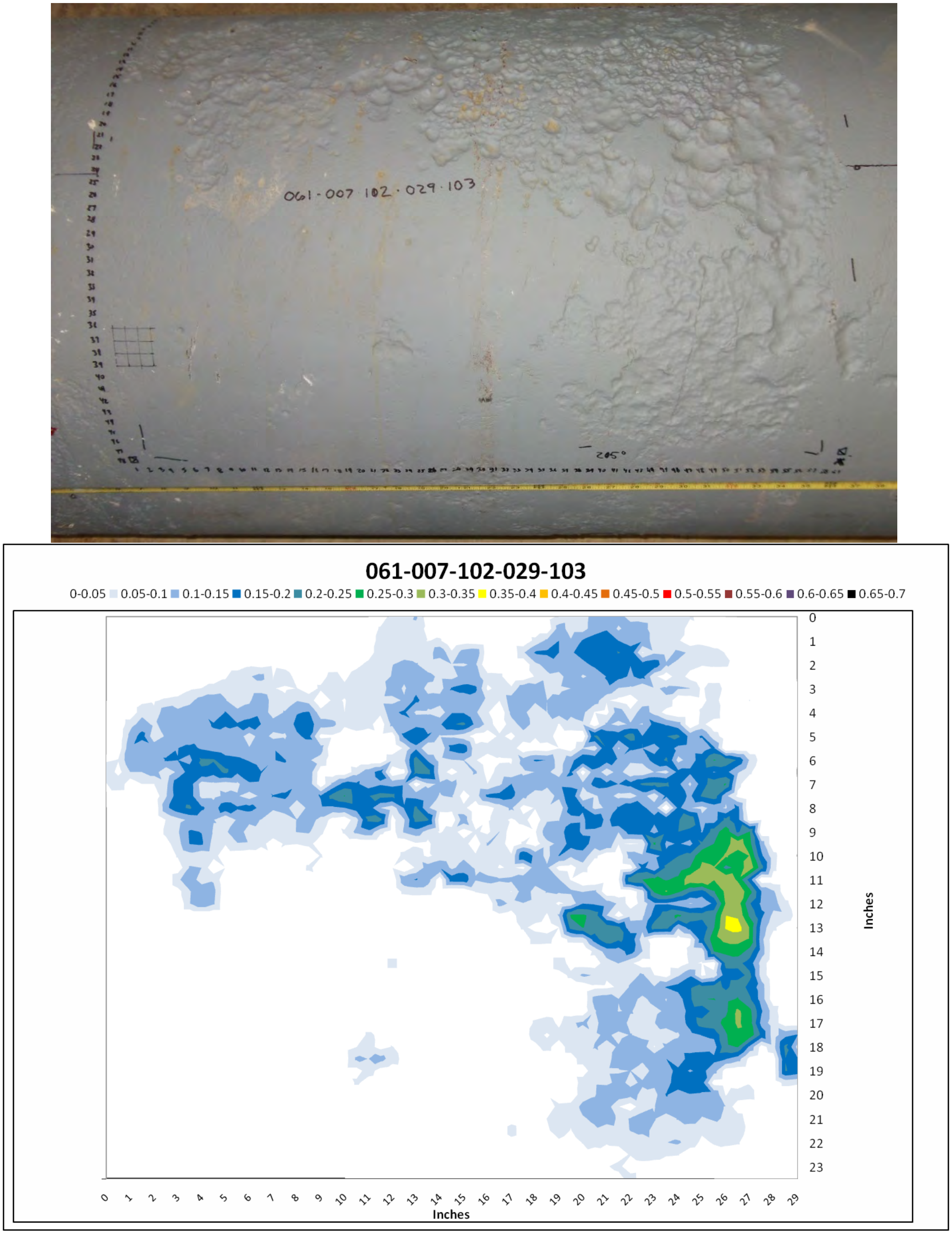
| | Outer Diameter | | |
|---|---|---|---|
| Pipe Number | Spigot | Center | Bell |
| 61 | 25.850 | 25.830 | 25.835 |

**Table A-61(4). Wall Thickness of Cement Liner at Spigot with Caliper**

| Measurement (Inches) | 0° | 90° | 205° | 280° |
|---|---|---|---|---|
| **Cast Iron** | 0.803 | 0.779 | 0.784 | 0.789 |
| **Cast Iron & Cement Liner** | 1.103 | 1.090 | 1.038 | 1.085 |
| **Cement Liner** | 0.300 | 0.311 | 0.254 | 0.296 |

## Table A-61(5). Pipe 61 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Bell (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| 061-099-097-020-051 | 12.8 | 38.5 | 0.396 | 51% | 0.38 | 49% | 216 | 7:12 |
| | | 43.5 | 0.268 | 34% | 0.51 | 66% | 252 | 8:24 |
| | | 37.0 | 0.258 | 33% | 0.52 | 67% | 214 | 7:08 |
| | | 40.0 | 0.247 | 32% | 0.53 | 68% | 232 | 7:44 |
| | | 40.0 | 0.211 | 27% | 0.57 | 73% | 223 | 7:26 |
| | | 40.0 | 0.210 | 27% | 0.57 | 73% | 250 | 8:20 |
| 061-119-100-017-114 | 21.2 | 23.5 | 0.492 | 63% | 0.29 | 37% | 200 | 6:40 |
| | | 23.0 | 0.436 | 56% | 0.34 | 44% | 193 | 6:26 |
| | | 23.0 | 0.425 | 54% | 0.36 | 46% | 185 | 6:10 |
| | | 26.0 | 0.318 | 41% | 0.46 | 59% | 207 | 6:54 |
| | | 21.5 | 0.308 | 39% | 0.47 | 61% | 180 | 6:00 |
| 061-082-150-013-072 | 11.9 | 60.5 | 0.488 | 63% | 0.29 | 38% | 175 | 5:50 |
| | | 60.5 | 0.409 | 52% | 0.37 | 48% | 168 | 5:36 |
| | | 58.5 | 0.374 | 48% | 0.41 | 52% | 203 | 6:46 |
| | | 60.0 | 0.367 | 47% | 0.41 | 53% | 186 | 6:12 |
| | | 65.0 | 0.254 | 33% | 0.53 | 68% | 150 | 5:00 |
| 061-058-182-025-060 | 23.6 | 72.0 | 0.319 | 41% | 0.46 | 59% | 171 | 5:42 |
| | | 84.5 | 0.314 | 40% | 0.47 | 60% | 171 | 5:42 |
| | | 71.0 | 0.279 | 36% | 0.50 | 64% | 167 | 5:34 |
| | | 75.0 | 0.247 | 32% | 0.53 | 68% | 158 | 5:16 |
| | | 88.0 | 0.239 | 31% | 0.54 | 69% | 167 | 5:34 |
| 061-007-102-029-103 | 40.6 | 116.5 | 0.374 | 48% | 0.41 | 52% | 200 | 6:40 |
| | | 118.0 | 0.346 | 44% | 0.43 | 56% | 209 | 6:58 |
| | | 116.5 | 0.335 | 43% | 0.45 | 57% | 216 | 7:12 |
| | | 116.5 | 0.311 | 40% | 0.47 | 60% | 185 | 6:10 |
| | | 119.5 | 0.304 | 39% | 0.48 | 61% | 207 | 6:54 |
| 061-056-108-021-052 | 15.6 | 90.0 | 0.399 | 51% | 0.38 | 49% | 210 | 7:00 |
| | | 91.0 | 0.385 | 49% | 0.40 | 51% | 228 | 7:36 |
| | | 87.0 | 0.355 | 45% | 0.43 | 55% | 234 | 7:48 |
| | | 85.0 | 0.346 | 44% | 0.43 | 56% | 219 | 7:18 |
| | | 84.0 | 0.338 | 43% | 0.44 | 57% | 223 | 7:26 |
| | | 84.0 | 0.318 | 41% | 0.46 | 59% | 239 | 7:58 |



061-007-102-029-103

Figure A-61(1). Pipe 61, area 061-007-102-029-103

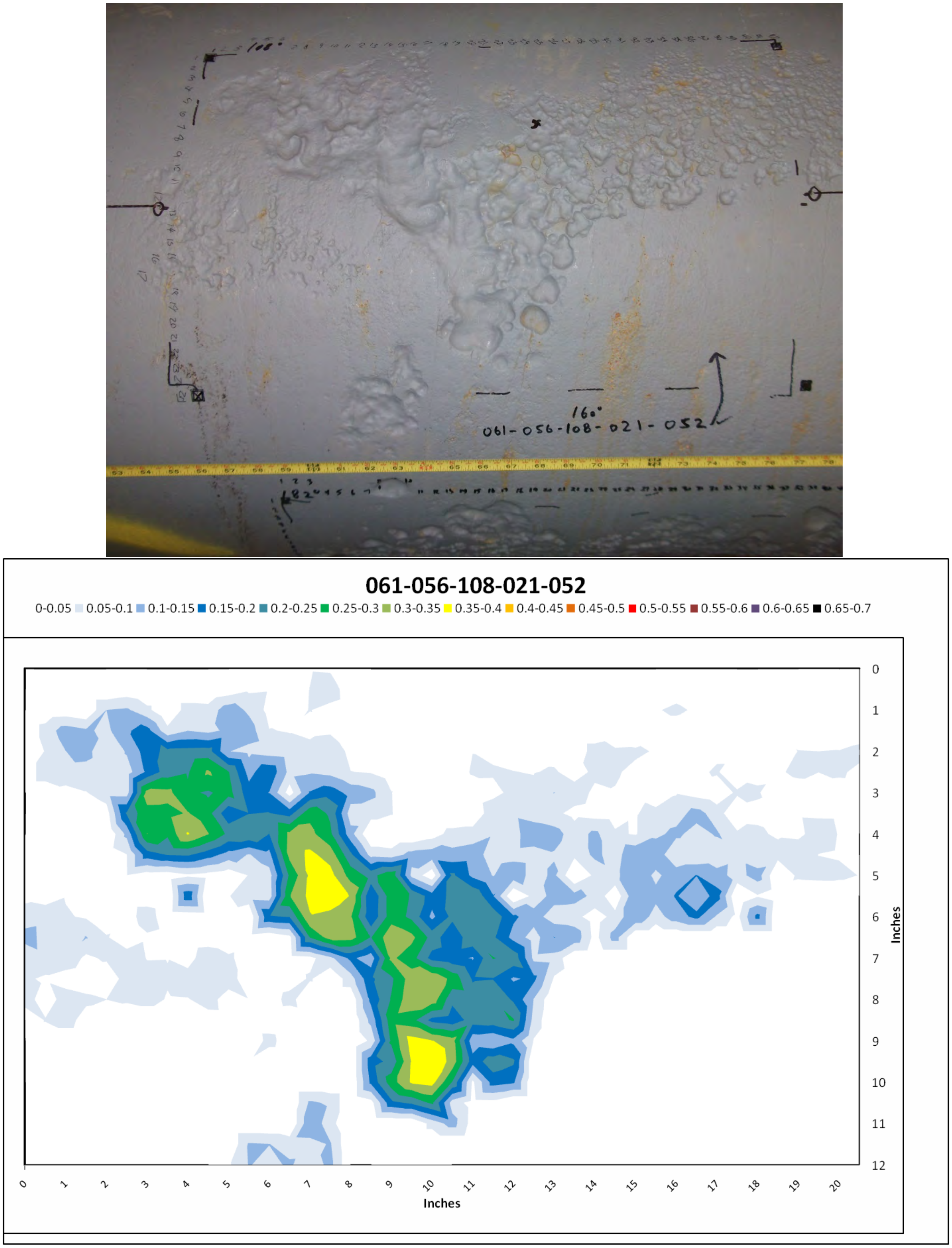


**Figure A-61(2). .Pipe 61, area 061-056-108-021-052**

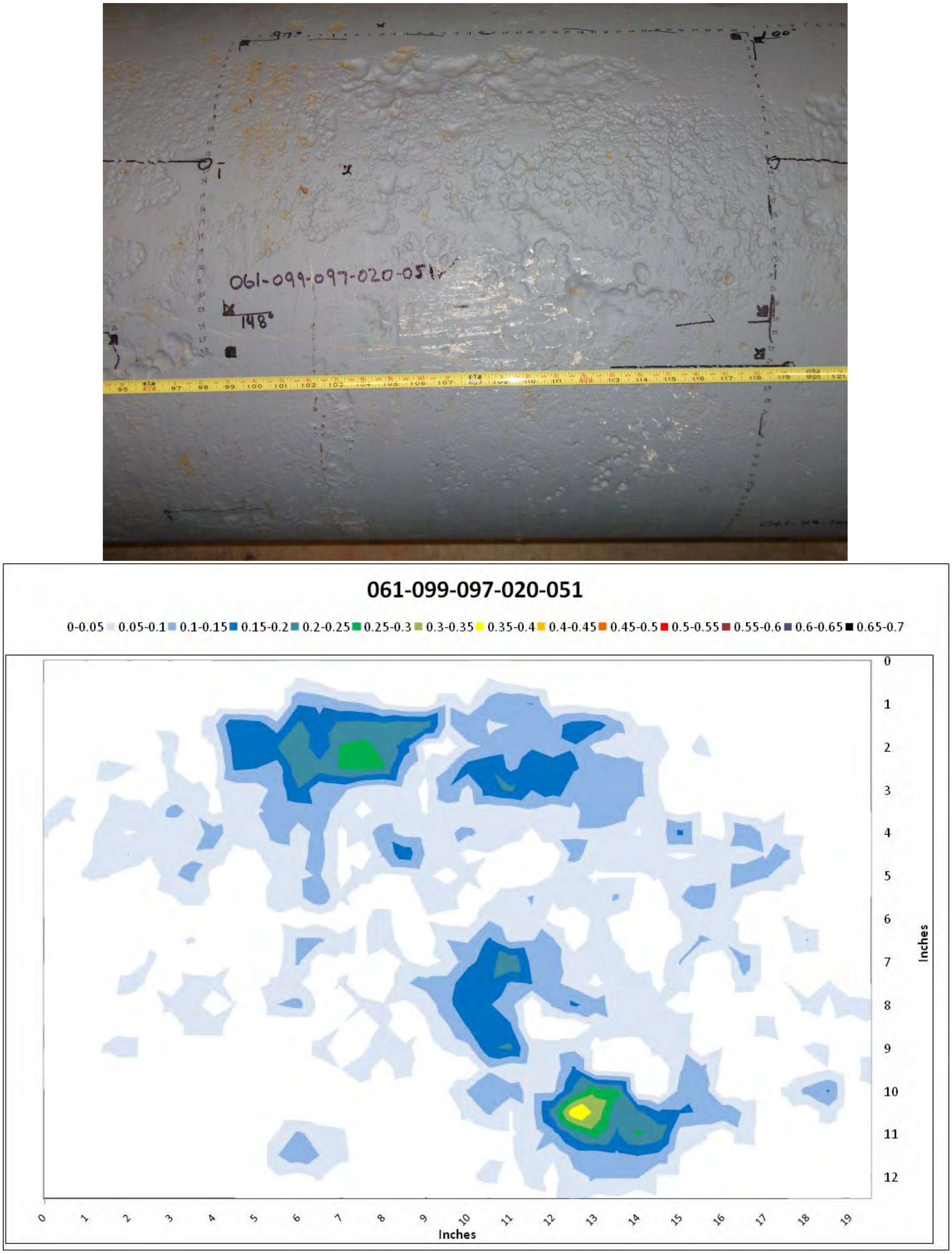


Figure A-61(3). Pipe 61, area 061-099-097-020-051

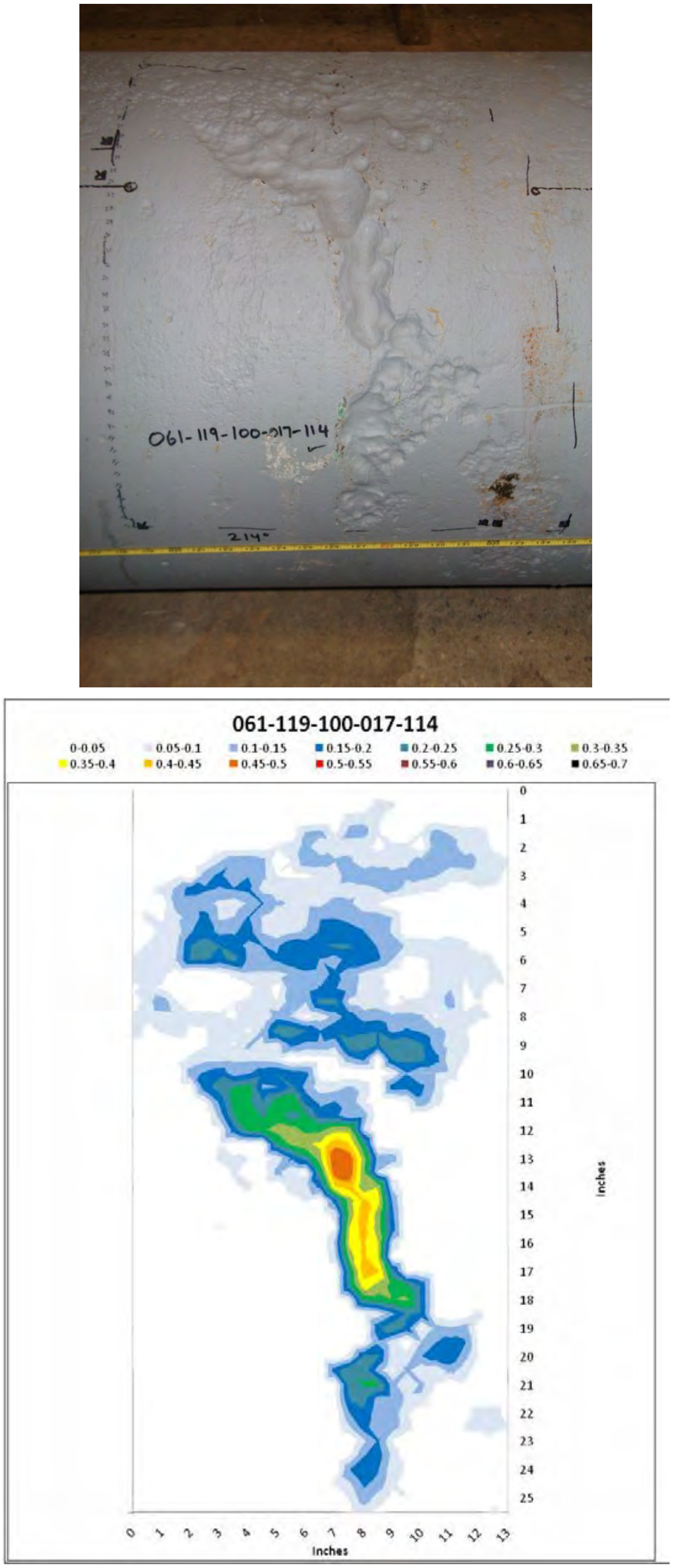


Figure A-61(4). Pipe 61, area 061-119-100-017-114

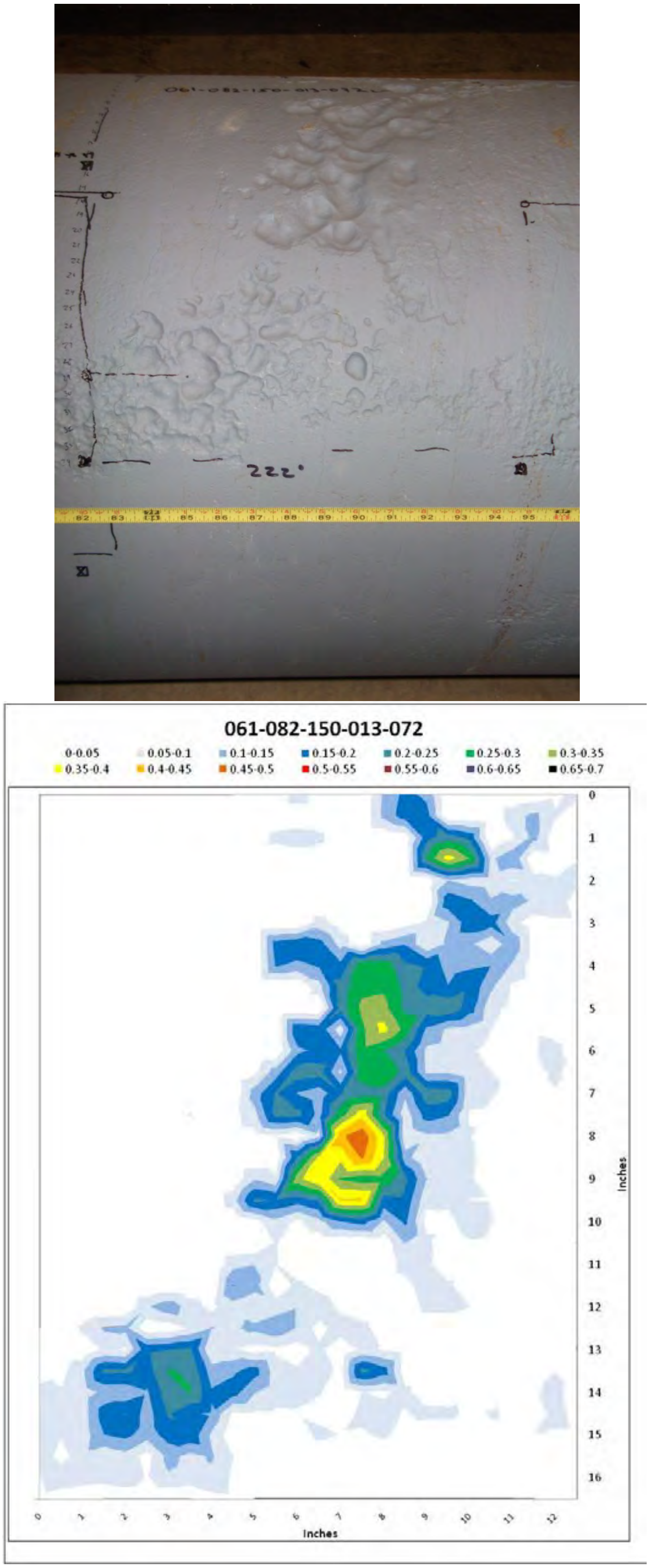


Figure A-61(5). Pipe 61, area 061-082-150-013-072

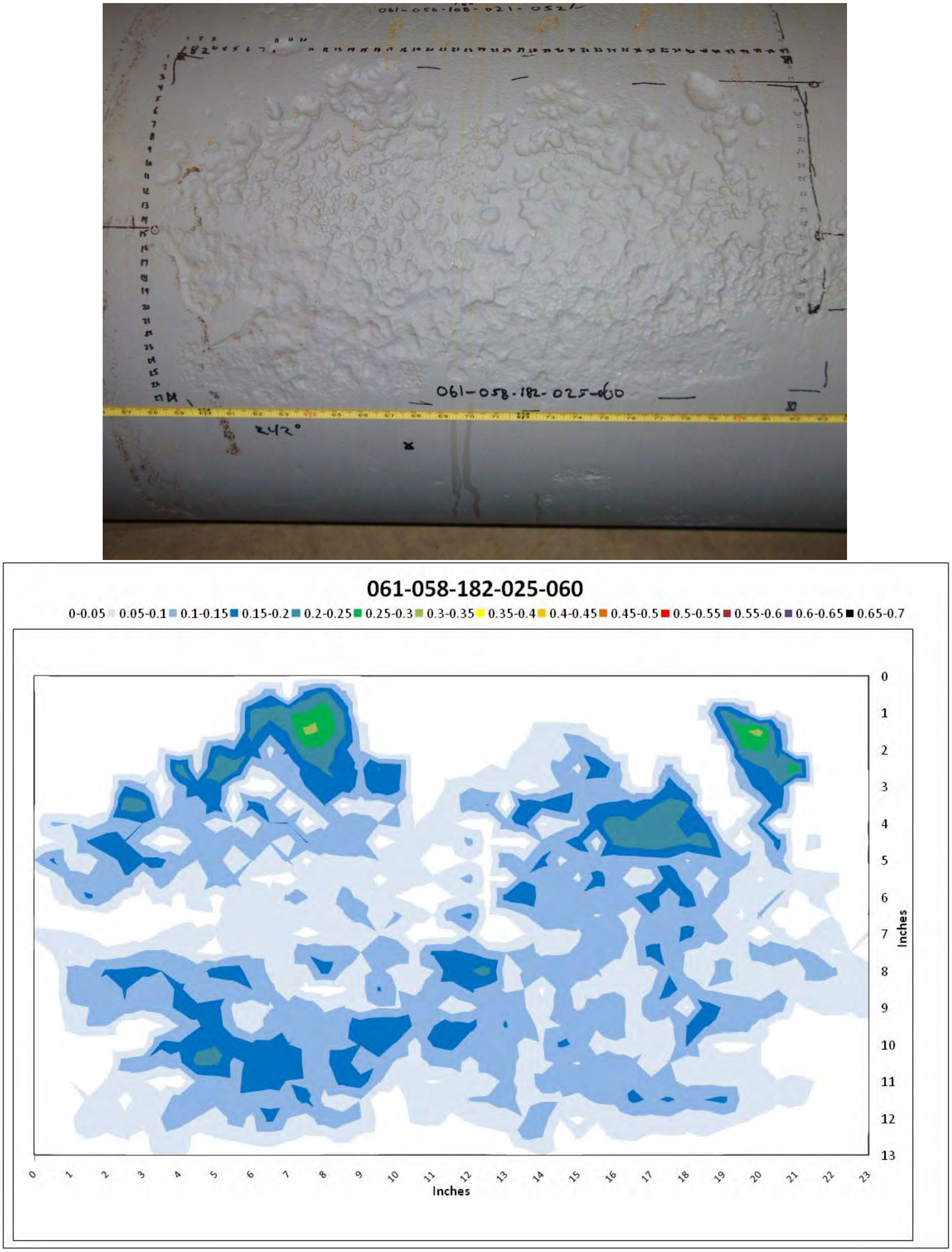


**Figure A-61(6). Pipe 61, area 061-058-182-025-060**

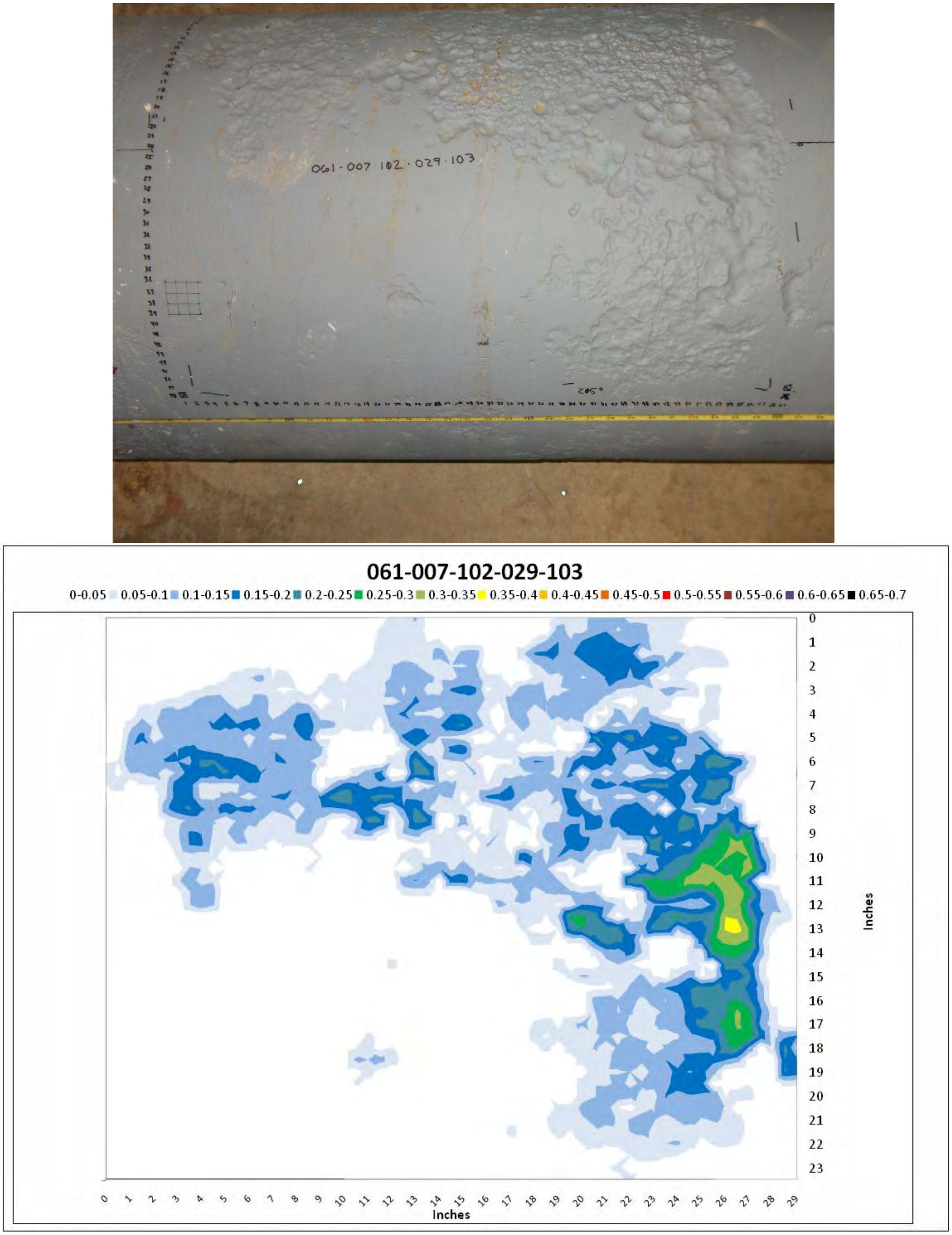


Figure A-61(7). Pipe 61, area 061-007-102-029-103

Figure A-63(1). Pipe 63 as Removed from Site

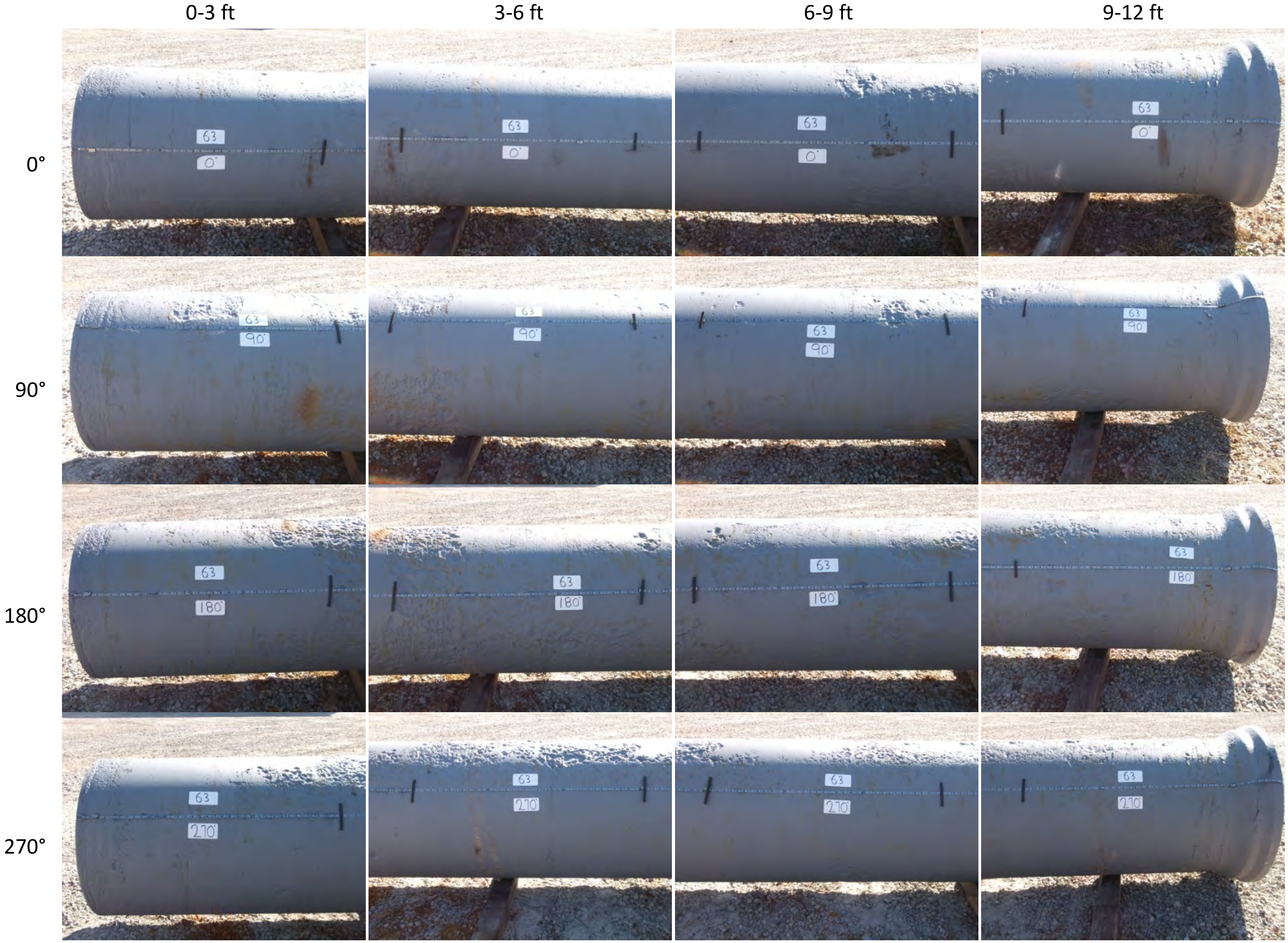


Figure A-63(2). Pipe 63 after Sandblasting

**Table A-63(1). Wall Thickness of Cast Iron at Spigot with Caliper**

| Pipe Number | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| | 45˚ | 140˚ | 230˚ | 240˚ |
| 63 | 0.813 | 0.818 | 0.816 | 0.813 |

**Table A-63(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)**

| Pipe Number | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| | Caliper | UT | | | UT | | | UT | | |
| 63 | 0.820 | 0.795 | 0.788 | 0.775 | 0.766 | 0.762 | 0.759 | 0.790 | 0.796 | 0.789 |
| | 0.817 | 0.783 | 0.788 | 0.791 | 0.764 | 0.760 | 0.755 | 0.787 | 0.817 | x |
| | 0.816 | 0.801 | 0.775 | 0.774 | 0.793 | 0.768 | 0.764 | 0.781 | 0.797 | x |
| **Average** | 0.818 | 0.786 | | | 0.766 | | | 0.794 | | |
| **Standard Deviation** | 0.002 | 0.010 | | | 0.011 | | | 0.012 | | |
| **Minimum** | 0.816 | 0.774 | | | 0.755 | | | 0.781 | | |
| **Maximum** | 0.820 | 0.801 | | | 0.793 | | | 0.817 | | |
| **Repeat Center Cell** | - | 0.785 | | | 0.770 | | | 0.805 | | |

**Table A-63(3). Outer Diameter Measurement Using a pi Tape**

| Pipe Number | Outer Diameter | | |
|---|---|---|---|
| | Spigot | Center | Bell |
| 63 | 25.800 | 25.775 | 25.775 |

**Table A-63(4). Wall Thickness of Cement Liner at Spigot with Caliper**

| Measurement (Inches) | 45˚ | 140˚ | 230˚ | 240˚ |
|---|---|---|---|---|
| **Cast Iron** | 0.813 | 0.818 | 0.816 | 0.813 |
| **Cast Iron & Cement Liner** | 1.087 | 1.067 | 1.099 | 1.154 |
| **Cement Liner** | 0.274 | 0.249 | 0.283 | 0.341 |

### Table A-63(5). Scanned Pipe 63 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Spigot (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| H22/H23 Comparison | 43.35 | 38.5 | 0.4004 | 51% | 0.3856 | 49% | 171 | 5:42 |
| | | 47.0 | 0.3957 | 50% | 0.3903 | 50% | 180 | 6:00 |
| | | 40.5 | 0.3339 | 42% | 0.4521 | 58% | 164 | 5:28 |
| | | 37.0 | 0.3327 | 42% | 0.4533 | 58% | 162 | 5:24 |
| | | 44.0 | 0.3323 | 42% | 0.4537 | 58% | 133 | 4:26 |
| | | 38.0 | 0.3087 | 39% | 0.4773 | 61% | 178 | 5:56 |
| | | 43.5 | 0.3075 | 39% | 0.4785 | 61% | 124 | 4:08 |
| | | 45.0 | 0.2992 | 38% | 0.4868 | 62% | 156 | 5:12 |
| | | 42.5 | 0.2894 | 37% | 0.4966 | 63% | 129 | 4:18 |
| | | 40.5 | 0.2819 | 36% | 0.5041 | 64% | 126 | 4:12 |
| | | 42.5 | 0.2728 | 35% | 0.5132 | 65% | 160 | 5:20 |
| | | 42.5 | 0.2673 | 34% | 0.5187 | 66% | 171 | 5:42 |
| | | 46.5 | 0.2642 | 34% | 0.5218 | 66% | 209 | 6:58 |
| | | 45.0 | 0.2441 | 31% | 0.5419 | 69% | 202 | 6:44 |
| | | 45.0 | 0.2370 | 30% | 0.5490 | 70% | 218 | 7:16 |
| | | 41.5 | 0.2299 | 29% | 0.5561 | 71% | 198 | 6:36 |
| | | 38.5 | 0.2268 | 29% | 0.5592 | 71% | 202 | 6:44 |
| | | 42.0 | 0.2142 | 27% | 0.5718 | 73% | 204 | 6:48 |
| | | 44.0 | 0.2063 | 26% | 0.5797 | 74% | 213 | 7:06 |
| | | 41.0 | 0.1811 | 23% | 0.6049 | 77% | 218 | 7:16 |
| | | 46.0 | 0.1780 | 23% | 0.6080 | 77% | 218 | 7:16 |
| H11 | 28.9 | 13.7 | 0.2035 | 26% | 0.5825 | 74% | 49 | 1:37 |
| | | 18.2 | 0.2299 | 29% | 0.5561 | 71% | 67 | 2:13 |
| | | 20.2 | 0.2465 | 31% | 0.5395 | 69% | 53 | 1:46 |
| | | 40.7 | 0.2579 | 33% | 0.5281 | 67% | 58 | 1:55 |
| | | 37.2 | 0.2803 | 36% | 0.5057 | 64% | 16 | 0:31 |
| | | 41.7 | 0.3024 | 38% | 0.4836 | 62% | 2 | 0:04 |
| H12 | 32.1 | 36.7 | 0.3327 | 42% | 0.4533 | 58% | 162 | 5:23 |
| | | 38.2 | 0.4004 | 51% | 0.3856 | 49% | 171 | 5:42 |
| | | 40.7 | 0.3339 | 42% | 0.4521 | 58% | 164 | 5:28 |
| | | 40.7 | 0.2819 | 36% | 0.5041 | 64% | 126 | 4:12 |
| H13 | 17.4 | 32.7 | 0.2472 | 31% | 0.5388 | 69% | 240 | 7:59 |
| | | 34.7 | 0.2488 | 32% | 0.5372 | 68% | 242 | 8:04 |
| | | 38.7 | 0.2764 | 35% | 0.5096 | 65% | 227 | 7:33 |
| | | 38.7 | 0.2268 | 29% | 0.5592 | 71% | 202 | 6:44 |
| | | 41.7 | 0.2299 | 29% | 0.5561 | 71% | 198 | 6:35 |
| | | 38.2 | 0.3205 | 41% | 0.4655 | 59% | 178 | 5:55 |
| | | 39.7 | 0.2795 | 36% | 0.5065 | 64% | 178 | 5:55 |
| H14 | 4.3 | 5.7 | 0.2358 | 30% | 0.5502 | 70% | 269 | 8:57 |
| | | 28.7 | 0.2921 | 37% | 0.4939 | 63% | 291 | 9:41 |
| | | 41.7 | 0.2835 | 36% | 0.5025 | 64% | 351 | 11:41 |
| H21 | 10.7 | 37.0 | 0.2803 | 36% | 0.5057 | 64% | 16 | 0:31 |

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Spigot (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| | | 42.0 | 0.3024 | 38% | 0.4836 | 62% | 2 | 0:04 |
| | | 43.5 | 0.2236 | 28% | 0.5624 | 72% | 9 | 0:17 |
| | | 39.5 | 0.2642 | 34% | 0.5218 | 66% | 62 | 2:04 |
| H22 | 50.1 | 40.5 | 0.2819 | 36% | 0.5041 | 64% | 126 | 4:12 |
| | | 43.5 | 0.3075 | 39% | 0.4785 | 61% | 124 | 4:08 |
| | | 42.5 | 0.2894 | 37% | 0.4966 | 63% | 129 | 4:18 |
| | | 44 | 0.3323 | 42% | 0.4537 | 58% | 133 | 4:26 |
| | | 45 | 0.2992 | 38% | 0.4868 | 62% | 156 | 5:12 |
| | | 42.5 | 0.2728 | 35% | 0.5132 | 65% | 160 | 5:20 |
| | | 40.5 | 0.3339 | 42% | 0.4521 | 58% | 164 | 5:28 |
| | | 37.0 | 0.3327 | 42% | 0.4533 | 58% | 162 | 5:24 |
| | | 42.5 | 0.2673 | 34% | 0.5187 | 66% | 171 | 5:42 |
| | | 38.5 | 0.4004 | 51% | 0.3856 | 49% | 171 | 5:42 |
| | | 46.0 | 0.2713 | 35% | 0.5147 | 65% | 166 | 5:32 |
| | | 51.5 | 0.2602 | 33% | 0.5258 | 67% | 171 | 5:42 |
| | | 54.5 | 0.2464 | 31% | 0.5396 | 69% | 173 | 5:46 |
| | | 66.0 | 0.5626 | 72% | 0.2234 | 28% | 171 | 5:41 |
| | | 58.5 | 0.2575 | 33% | 0.5285 | 67% | 173 | 5:46 |
| H23 | 40.3 | 47.0 | 0.3957 | 50% | 0.3903 | 50% | 180 | 6:00 |
| | | 38.0 | 0.3087 | 39% | 0.4773 | 61% | 178 | 5:56 |
| | | 45.0 | 0.2441 | 31% | 0.5419 | 69% | 202 | 6:44 |
| | | 42.0 | 0.2142 | 27% | 0.5718 | 73% | 204 | 6:48 |
| | | 41.5 | 0.2299 | 29% | 0.5561 | 71% | 198 | 6:36 |
| | | 38.5 | 0.2268 | 29% | 0.5592 | 71% | 202 | 6:44 |
| | | 46.5 | 0.2642 | 34% | 0.5218 | 66% | 209 | 6:58 |
| | | 44.0 | 0.2063 | 26% | 0.5797 | 74% | 213 | 7:06 |
| | | 46.0 | 0.1780 | 23% | 0.6080 | 77% | 218 | 7:16 |
| | | 45.0 | 0.2370 | 30% | 0.5490 | 70% | 218 | 7:16 |
| | | 41.0 | 0.1811 | 23% | 0.6049 | 77% | 218 | 7:16 |
| | | 38.5 | 0.2677 | 34% | 0.5183 | 66% | 229 | 7:37 |
| | | 54.5 | 0.3000 | 38% | 0.4860 | 62% | 186 | 6:12 |
| | | 56.5 | 0.2835 | 36% | 0.5025 | 64% | 191 | 6:21 |
| | | 57.0 | 0.2941 | 37% | 0.4919 | 63% | 180 | 5:59 |
| | | 65.0 | 0.4413 | 56% | 0.3447 | 44% | 178 | 5:55 |
| | | 70.5 | 0.2780 | 35% | 0.5080 | 65% | 211 | 7:01 |
| | | 69.0 | 0.2760 | 35% | 0.5100 | 65% | 209 | 6:57 |
| | | 63.5 | 0.2831 | 36% | 0.5029 | 64% | 218 | 7:16 |
| | | 61.5 | 0.3185 | 41% | 0.4675 | 59% | 215 | 7:10 |
| | | 59.0 | 0.2961 | 38% | 0.4899 | 62% | 224 | 7:28 |
| | | 57.0 | 0.2614 | 33% | 0.5246 | 67% | 204 | 6:48 |
| H24 | 7.2 | 42.0 | 0.2846 | 36% | 0.5014 | 64% | 351 | 11:41 |
| H31 | 9.2 | 95.0 | 0.2209 | 28% | 0.5651 | 72% | 42 | 1:24 |

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Spigot (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
|  |  | 100.5 | 0.2130 | 27% | 0.5730 | 73% | 40 | 1:20 |
|  |  | 101.5 | 0.2634 | 34% | 0.5226 | 66% | 67 | 2:13 |
|  |  | 108.0 | 0.2110 | 27% | 0.5750 | 73% | 53 | 1:46 |
| H32 | 11.2 | 74.0 | 0.4626 | 59% | 0.3234 | 41% | 138 | 4:35 |
|  |  | 74.0 | 0.2791 | 36% | 0.5069 | 64% | 149 | 4:57 |
|  |  | 75.5 | 0.2209 | 28% | 0.5651 | 72% | 171 | 5:42 |
|  |  | 95.9 | 0.3811 | 48% | 0.4049 | 52% | 178 | 5:55 |
|  |  | 104.0 | 0.3654 | 46% | 0.4206 | 54% | 178 | 5:55 |
| H33 | 22.8 | 73.0 | 0.3665 | 47% | 0.4195 | 53% | 218 | 7:16 |
|  |  | 95.9 | 0.4260 | 54% | 0.3600 | 46% | 180 | 6:00 |
|  |  | 98.0 | 0.3319 | 42% | 0.4541 | 58% | 180 | 6:00 |
|  |  | 104.0 | 0.3799 | 48% | 0.4061 | 52% | 178 | 5:56 |
|  |  | 104.4 | 0.4327 | 55% | 0.3533 | 45% | 193 | 6:26 |
| H34 | 28.5 | 93.5 | 0.2528 | 32% | 0.5332 | 68% | 295 | 9:50 |
|  |  | 97.4 | 0.2693 | 34% | 0.5167 | 66% | 309 | 10:18 |
|  |  | 95.5 | 0.3815 | 49% | 0.4045 | 51% | 311 | 10:22 |
|  |  | 95.9 | 0.3303 | 42% | 0.4557 | 58% | 318 | 10:35 |
| H41 | 10.5 | 107.0 | 0.2071 | 26% | 0.5789 | 74% | 51 | 1:42 |
|  |  | 110.0 | 0.2031 | 26% | 0.5829 | 74% | 44 | 1:28 |
| H42 | 44.1 | 113.0 | 0.3488 | 44% | 0.4372 | 56% | 160 | 5:19 |
|  |  | 114.1 | 0.3287 | 42% | 0.4573 | 58% | 178 | 5:55 |
|  |  | 119.0 | 0.3780 | 48% | 0.4080 | 52% | 169 | 5:38 |
|  |  | 125.0 | 0.4213 | 54% | 0.3647 | 46% | 169 | 5:38 |
| H43 | 27 | 114.1 | 0.3311 | 42% | 0.4549 | 58% | 178 | 5:56 |
|  |  | 115.6 | 0.5173 | 66% | 0.2687 | 34% | 191 | 6:21 |
|  |  | 121.1 | 0.3063 | 39% | 0.4797 | 61% | 189 | 6:18 |
|  |  | 126.6 | 0.3673 | 47% | 0.4187 | 53% | 198 | 6:36 |
| H44 | 14.4 | 110.5 | 0.1693 | 22% | 0.6167 | 78% | 326 | 10:52 |

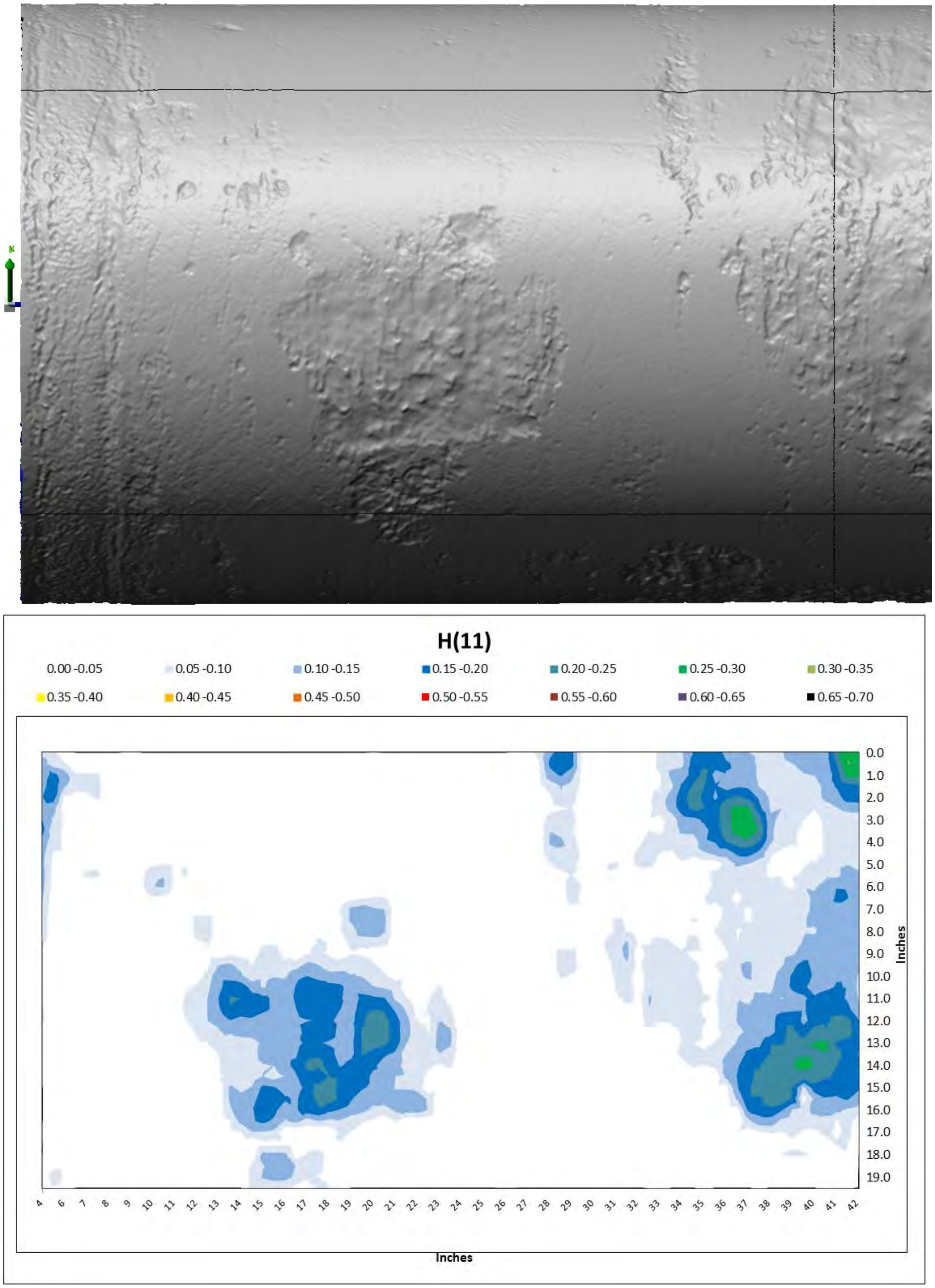


Figure A-63(1). Pipe 63, 0-3 feet and 0-90 degrees

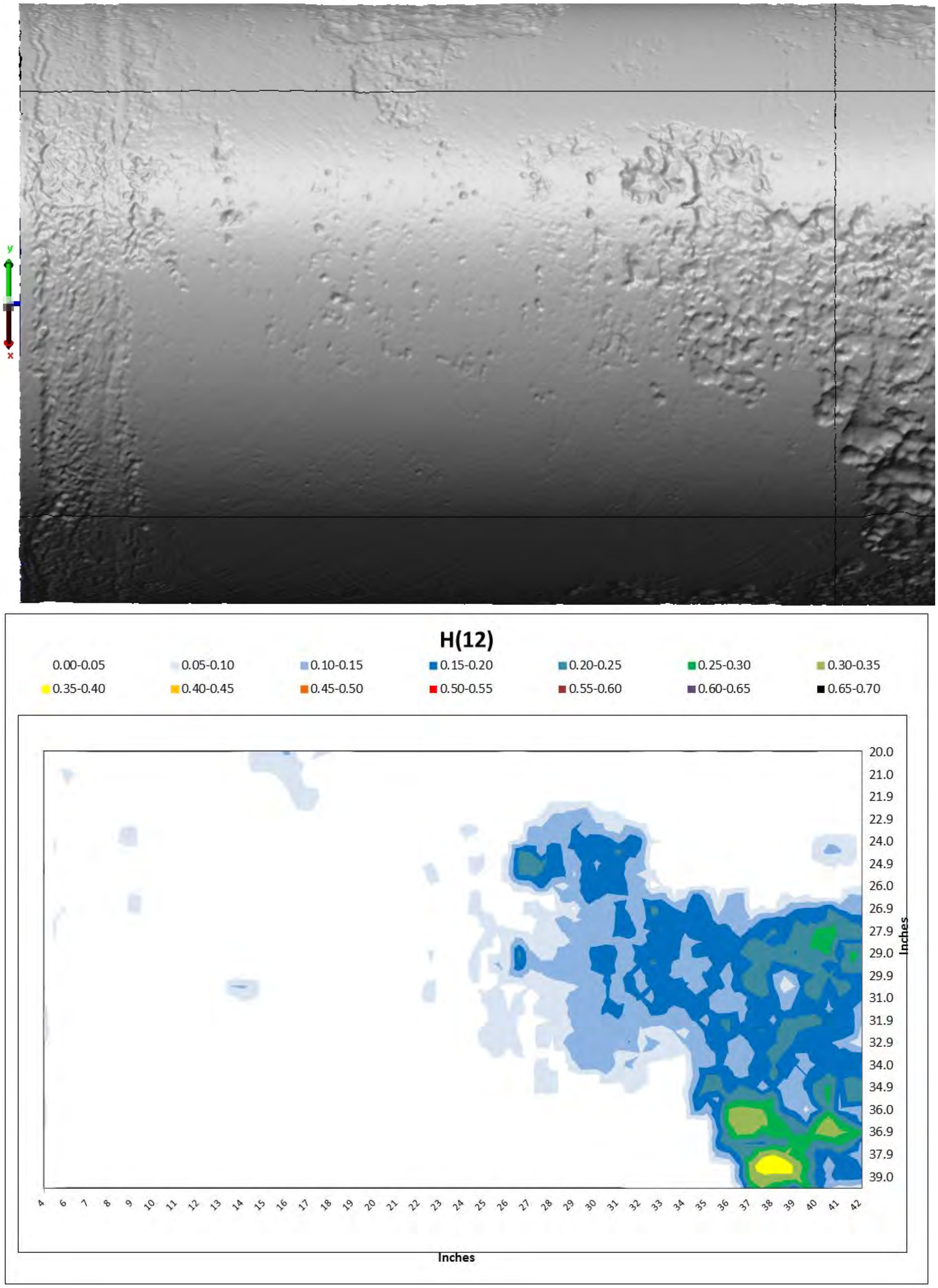


Figure A-63(2). Pipe 63, 0-3 feet and 90-180 degrees

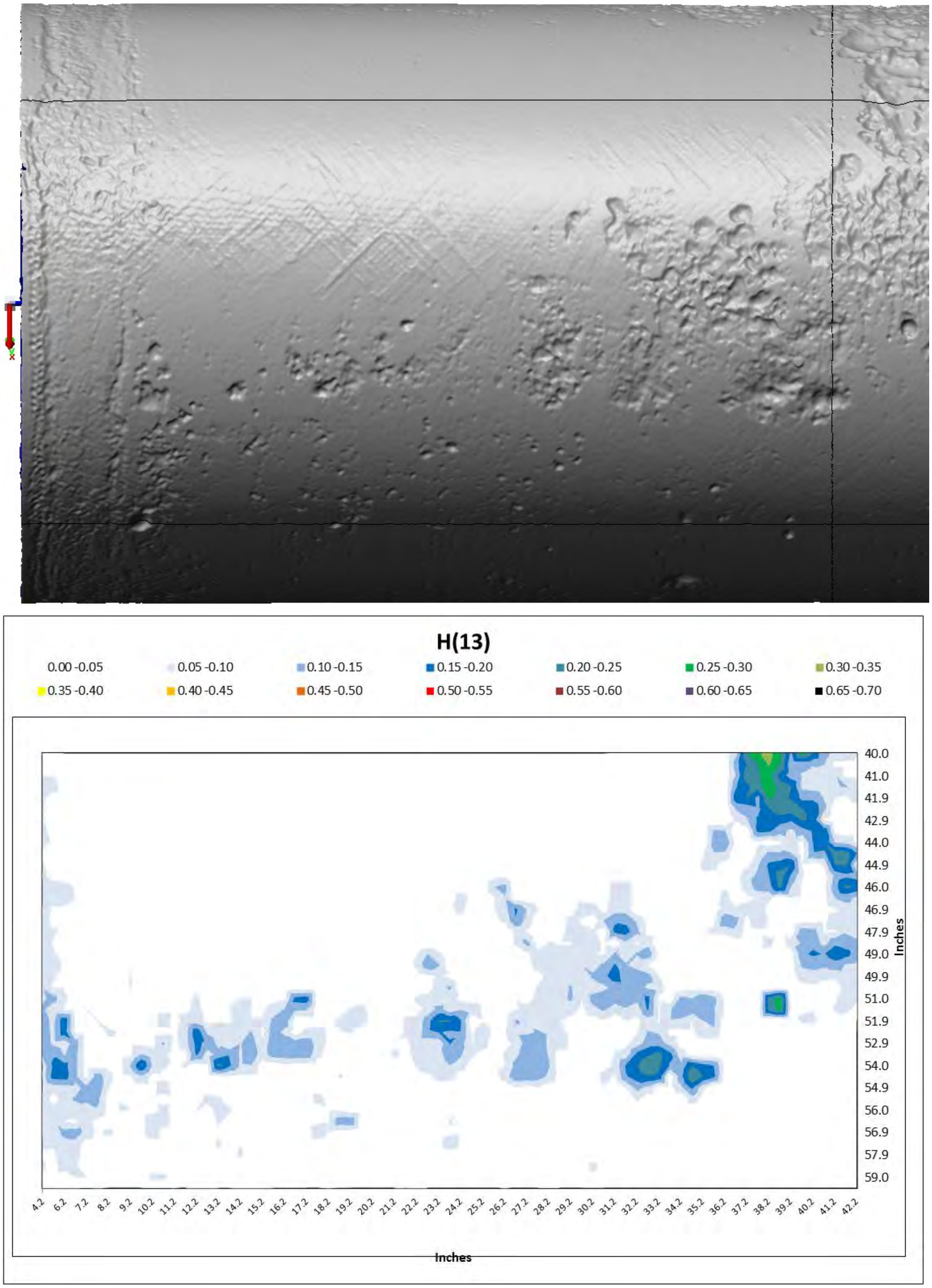


Figure A-63(3). Pipe 63, 0-3 feet and 180-270 degrees

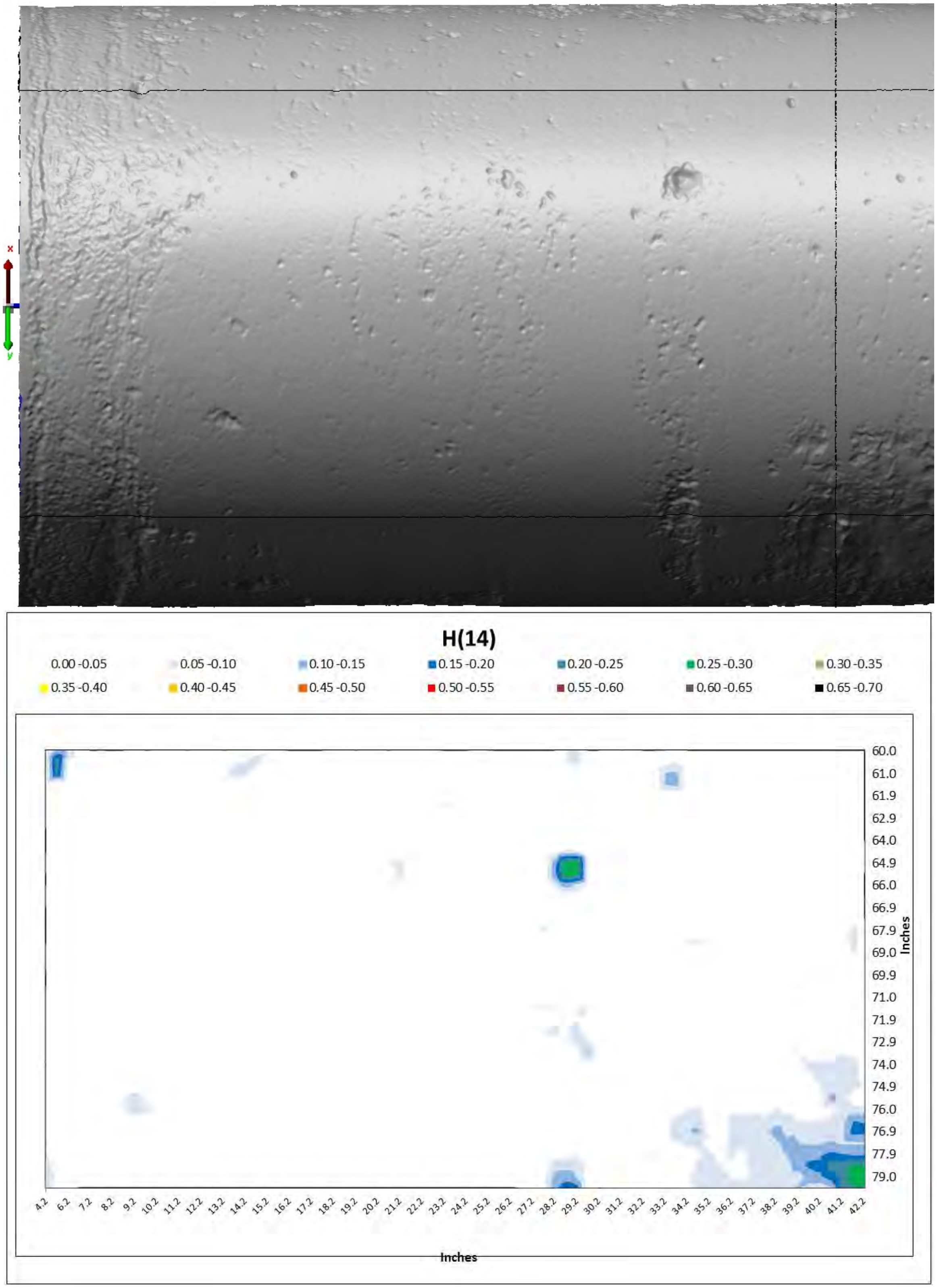


Figure A-63(4). Pipe 63, 0-3 feet and 270-300 degrees

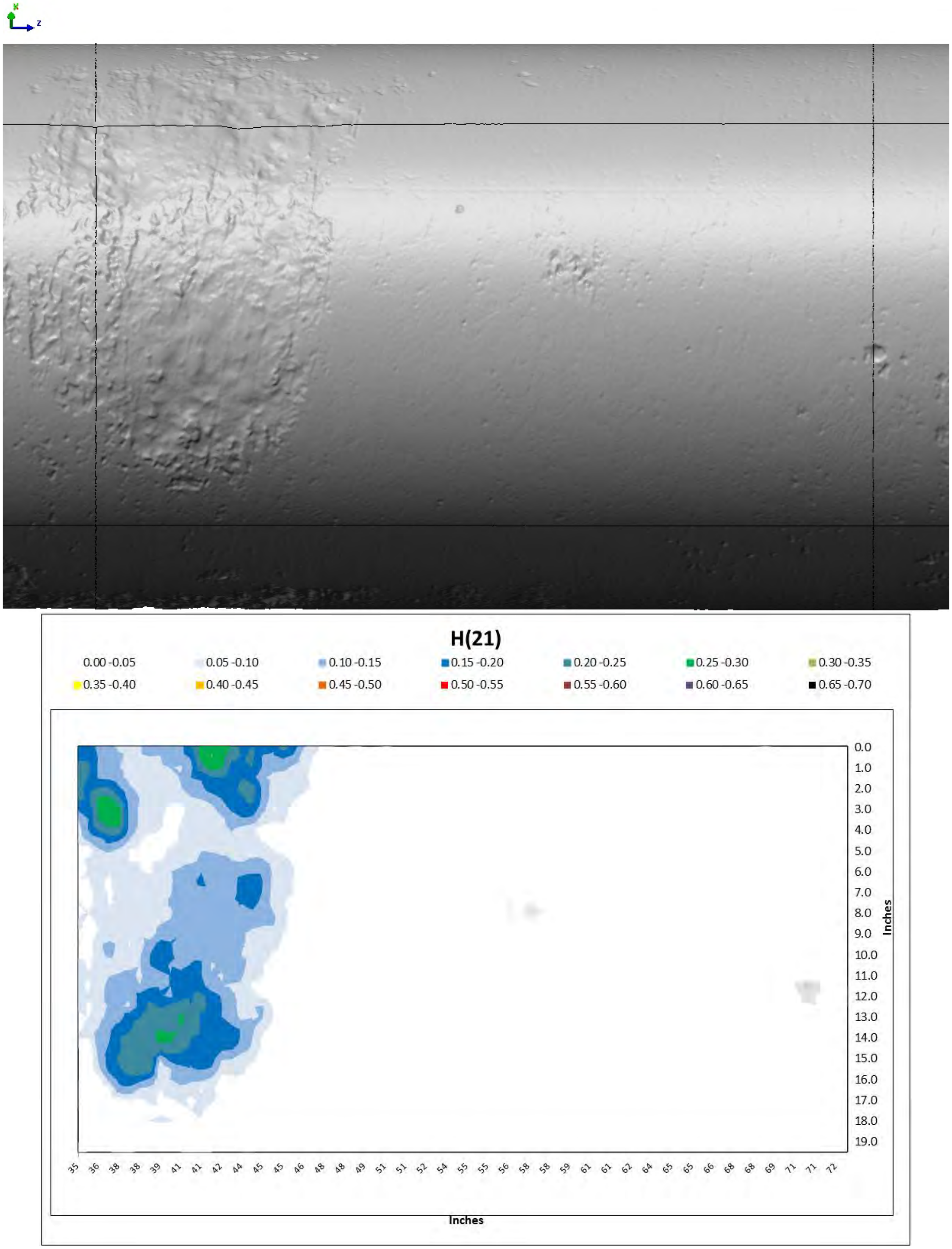


**Figure A-63(5). Pipe 63, 3-6 feet and 0-90 degrees**

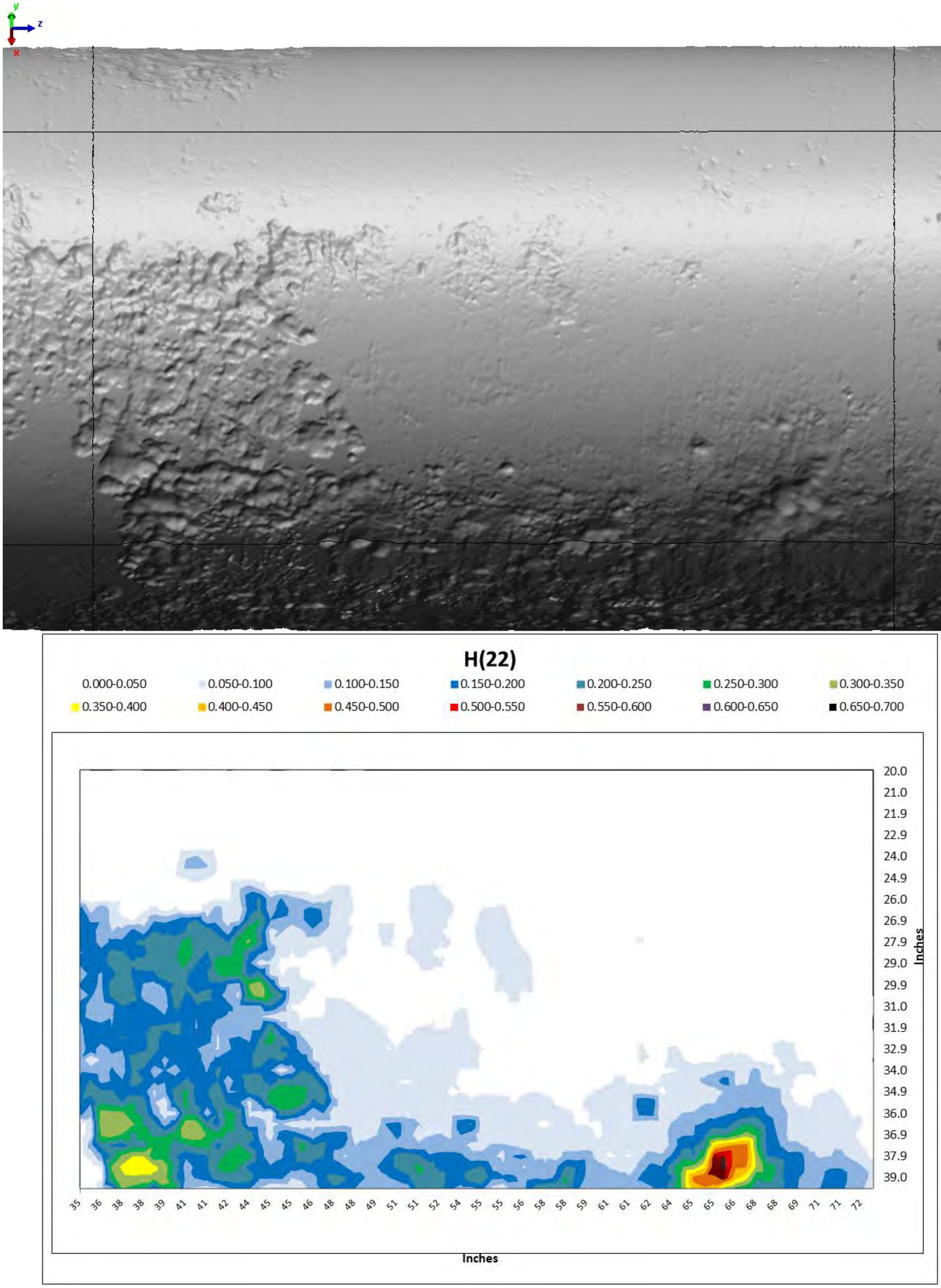


Figure A-63(8). Pipe 63, 3-6 feet and 90-180 degrees

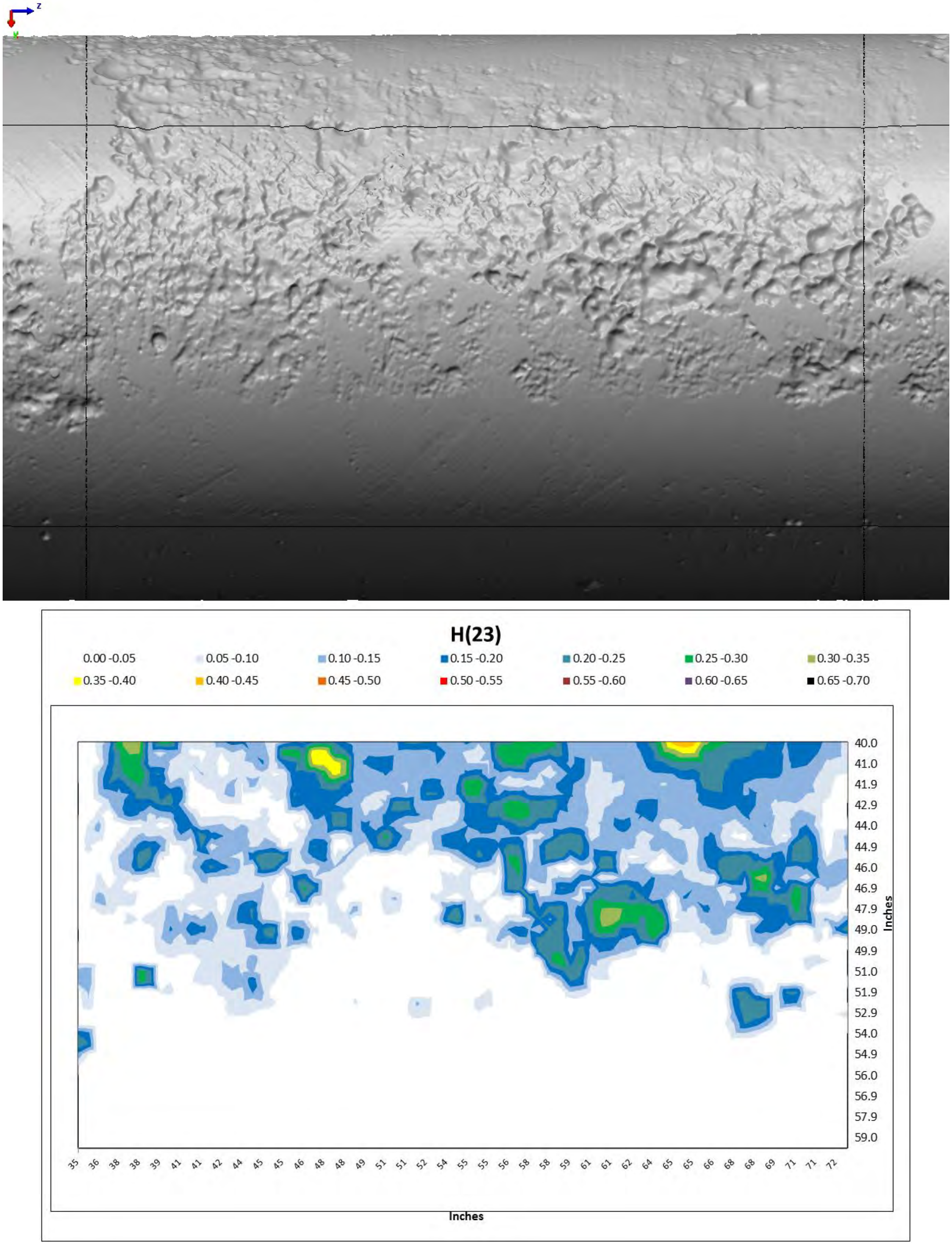


**Figure A-63(9). Pipe 63, 3-6 feet and 180-270 degrees**

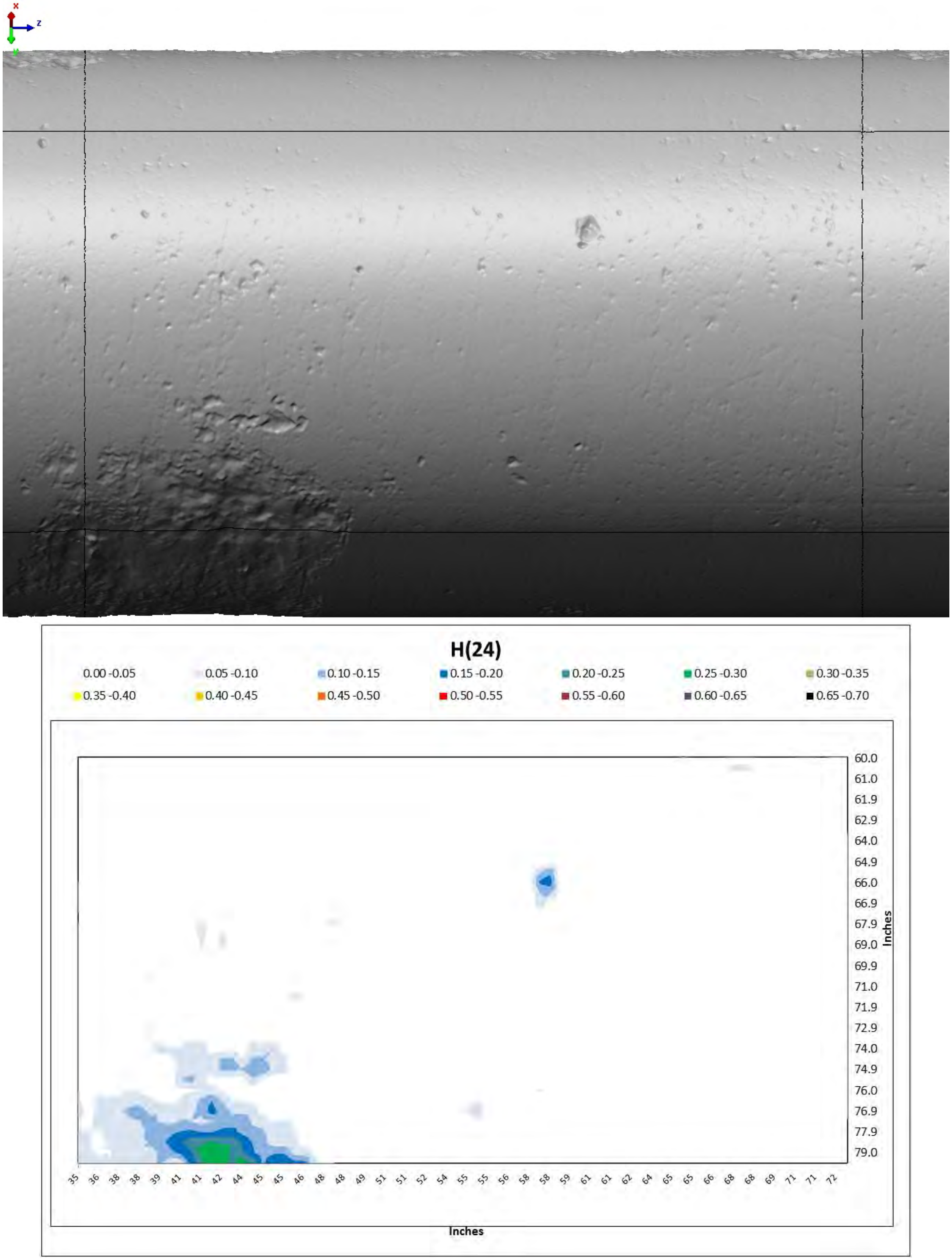


Figure A-63(10). Pipe 63, 3-6 feet and 270-300 degrees

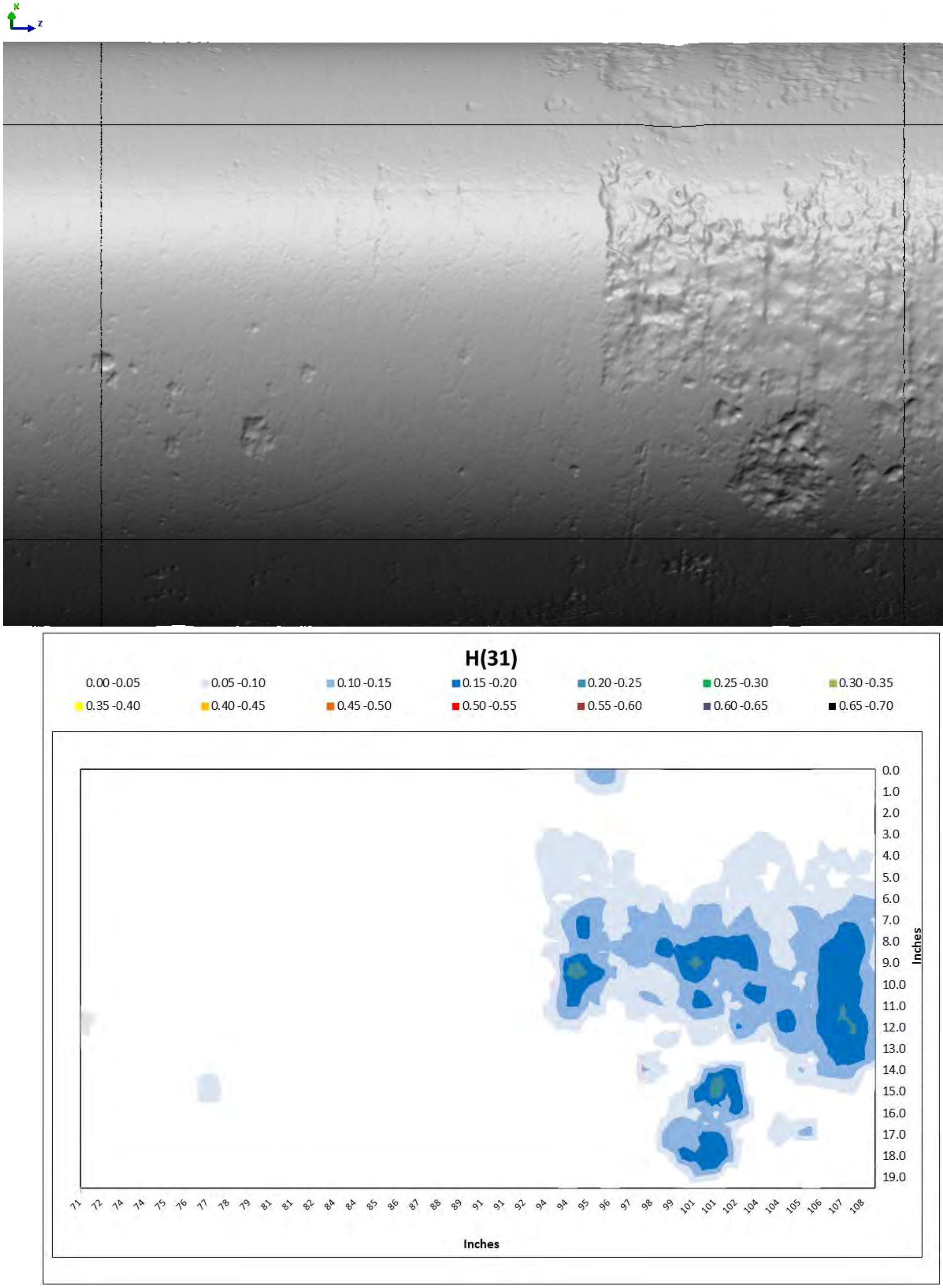


Figure A-63(11). Pipe 63, 6-9 feet and 0-90 degrees

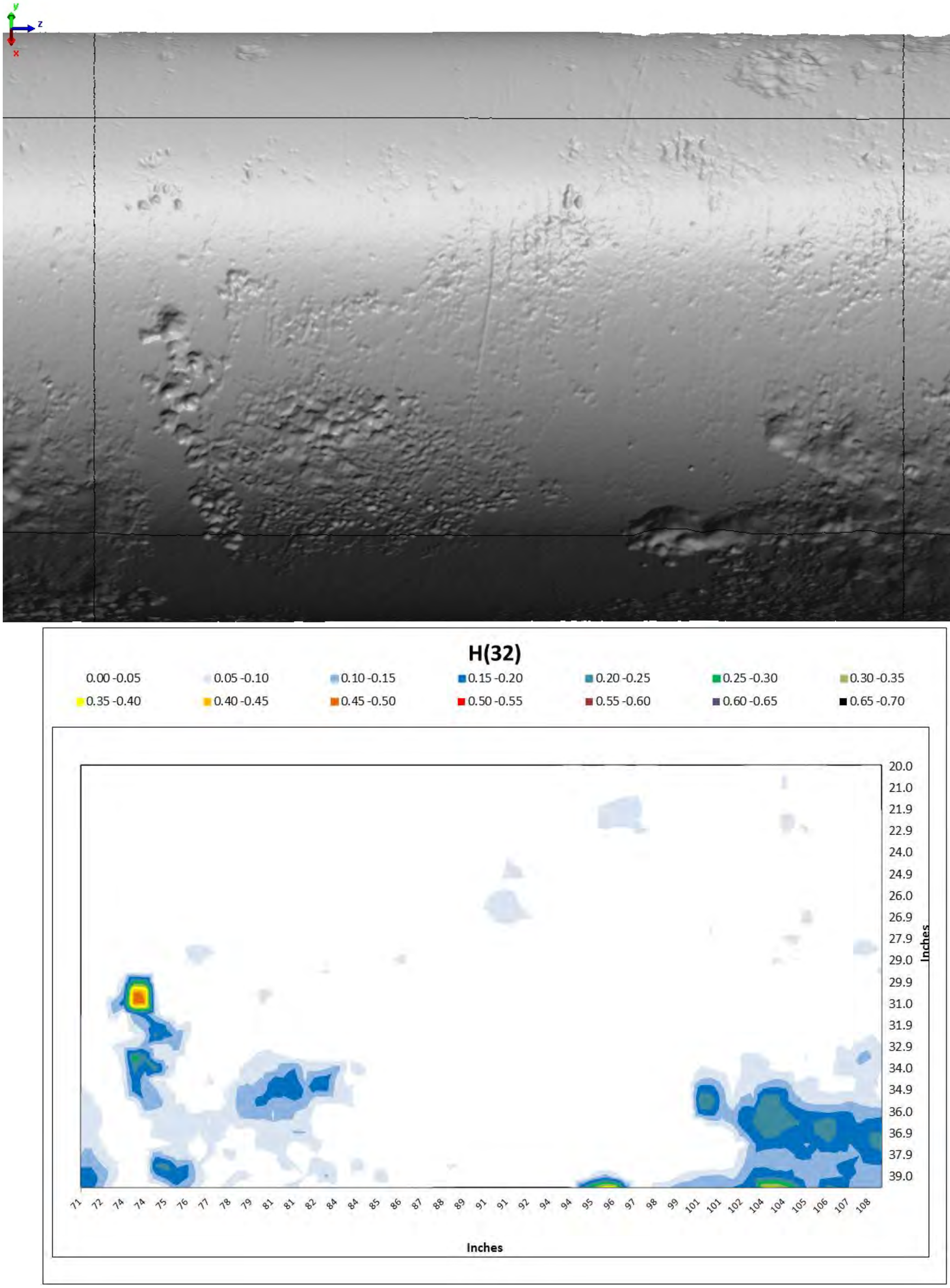


Figure A-63(12). Pipe 63, 6-9 feet and 90-180 degrees

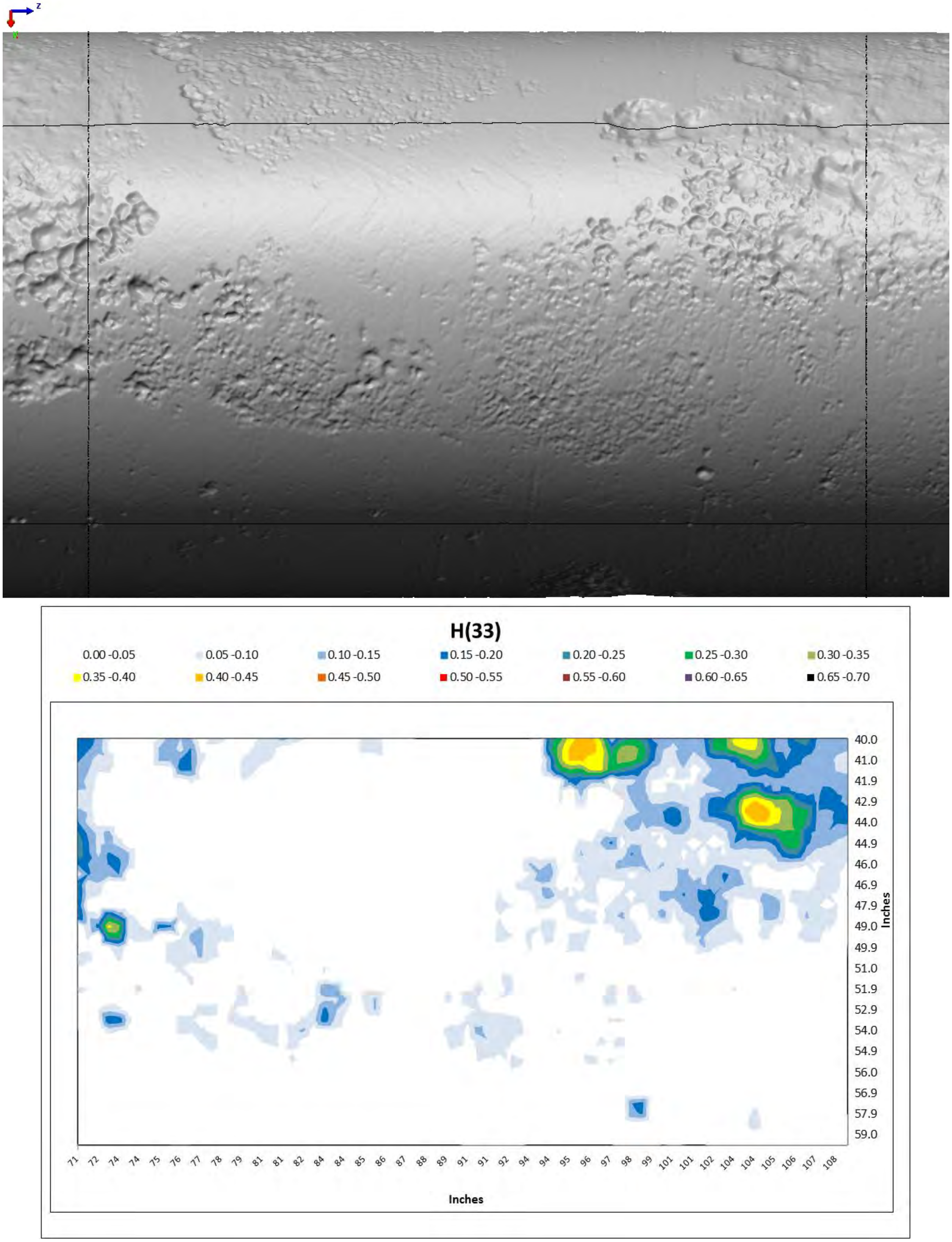


Figure A-63(13). Pipe 63, 6-9 feet and 180-270 degrees

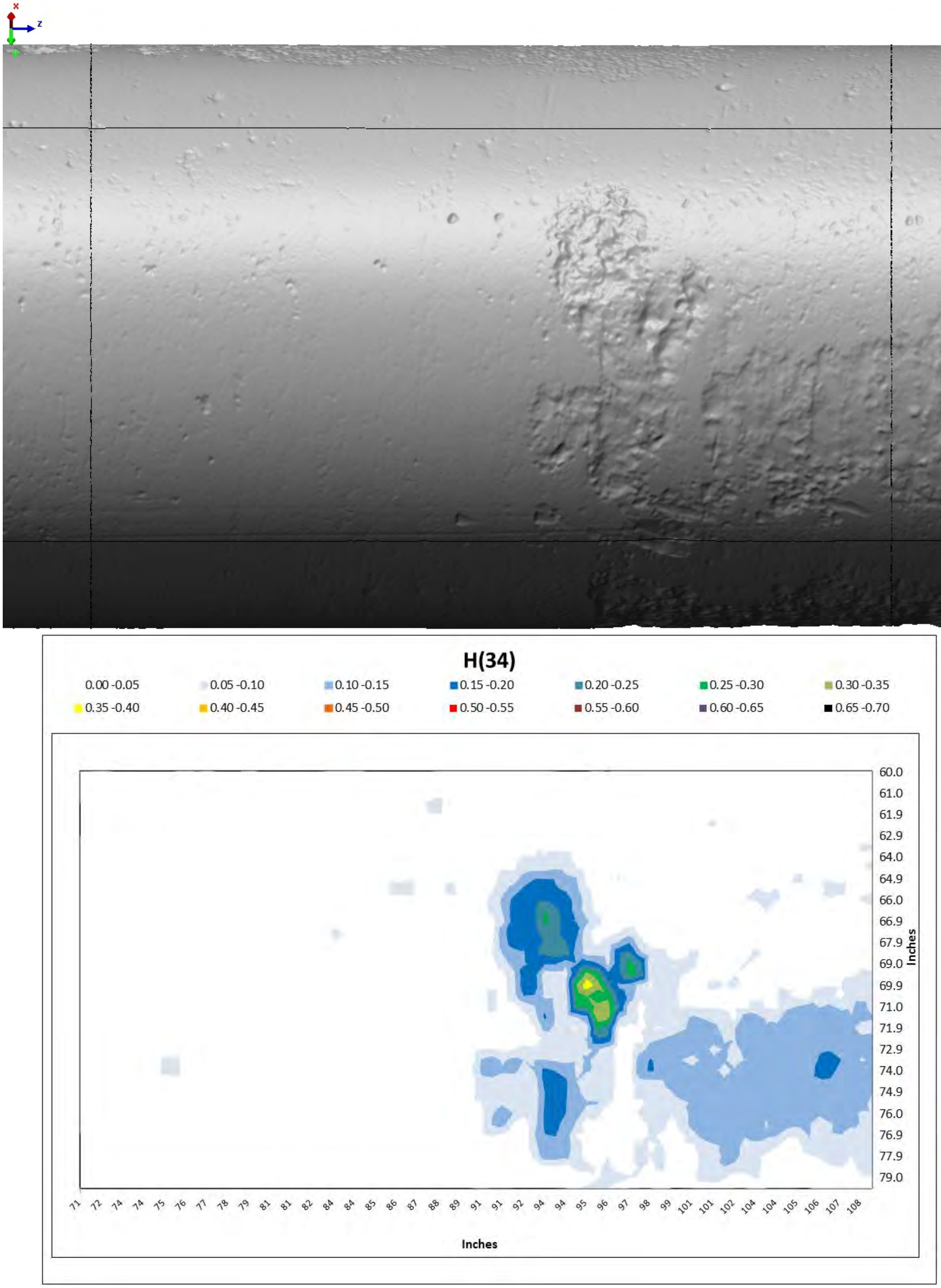


Figure A-63(14). Pipe 63, 6-9 feet and 270-300 degrees

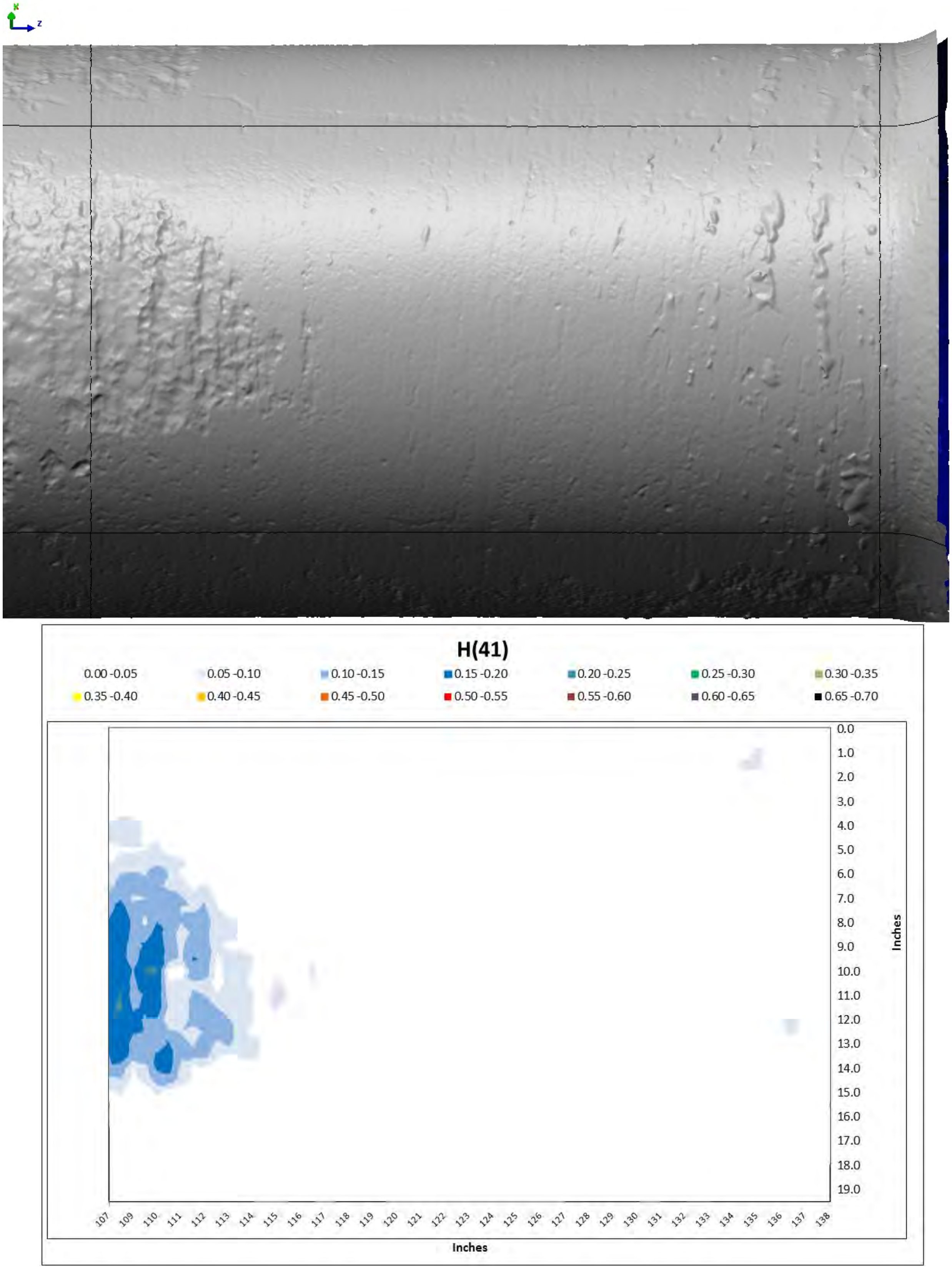


Figure A-63(15). Pipe 63, 9-12 feet and 0-90 degrees

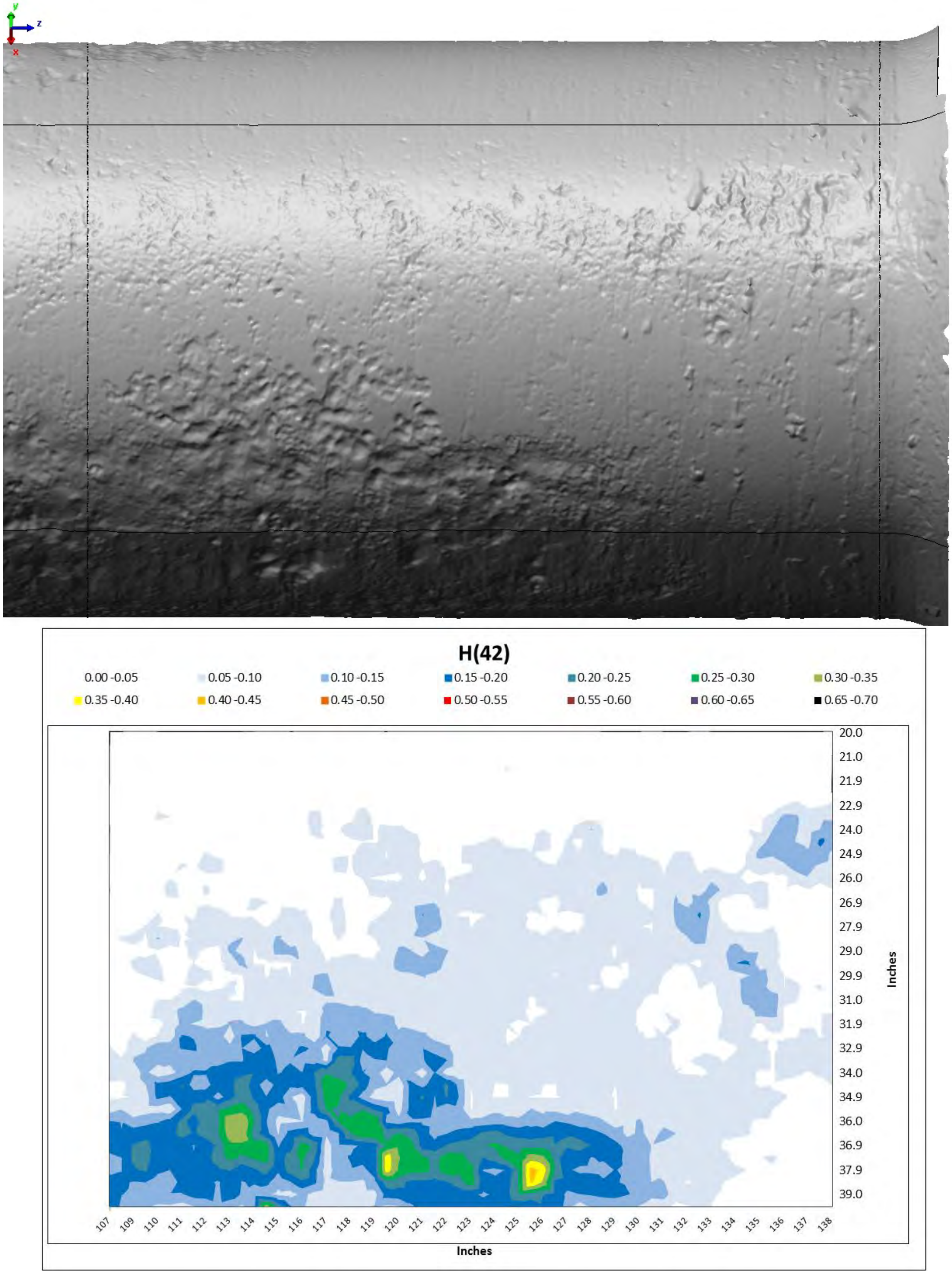


Figure A-63(16). Pipe 63, 9-12 feet and 90-180 degrees

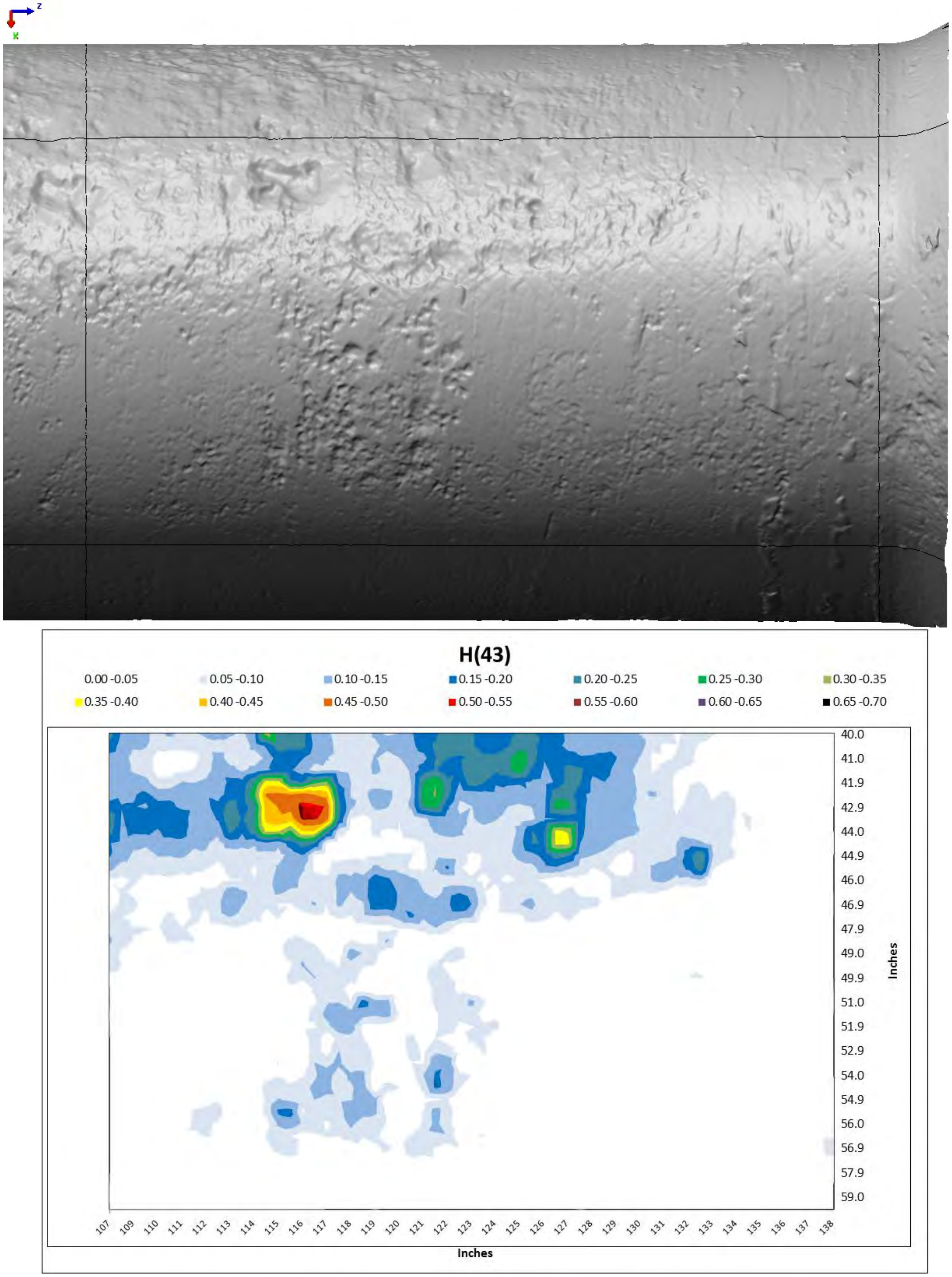


Figure A-63(17). Pipe 63, 9-12 feet and 180-270 degrees

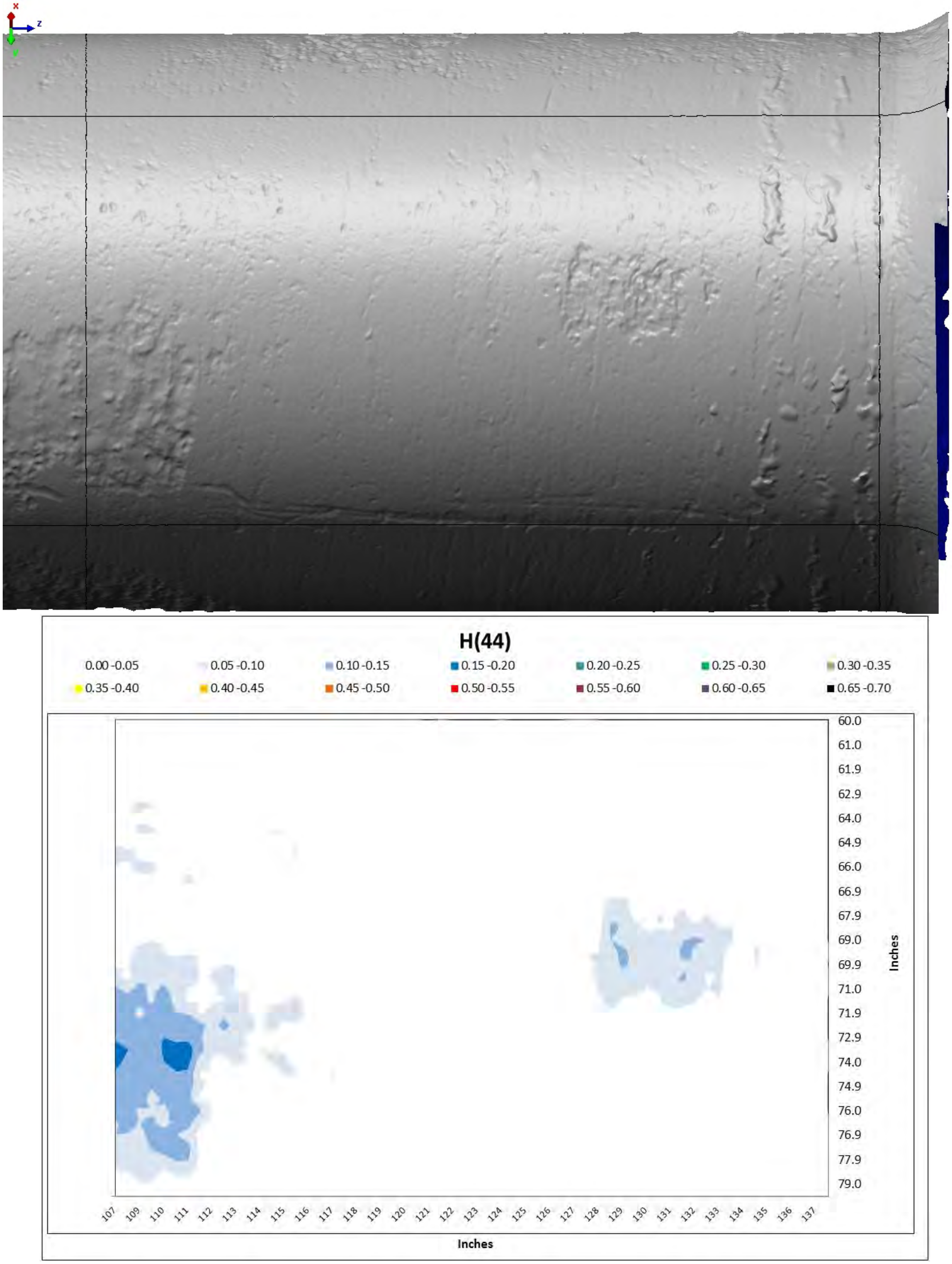


Figure A-63(18). Pipe 63, 9-12 feet and 270-300 degrees

Figure A-64(1). Pipe 64 as Removed from Site

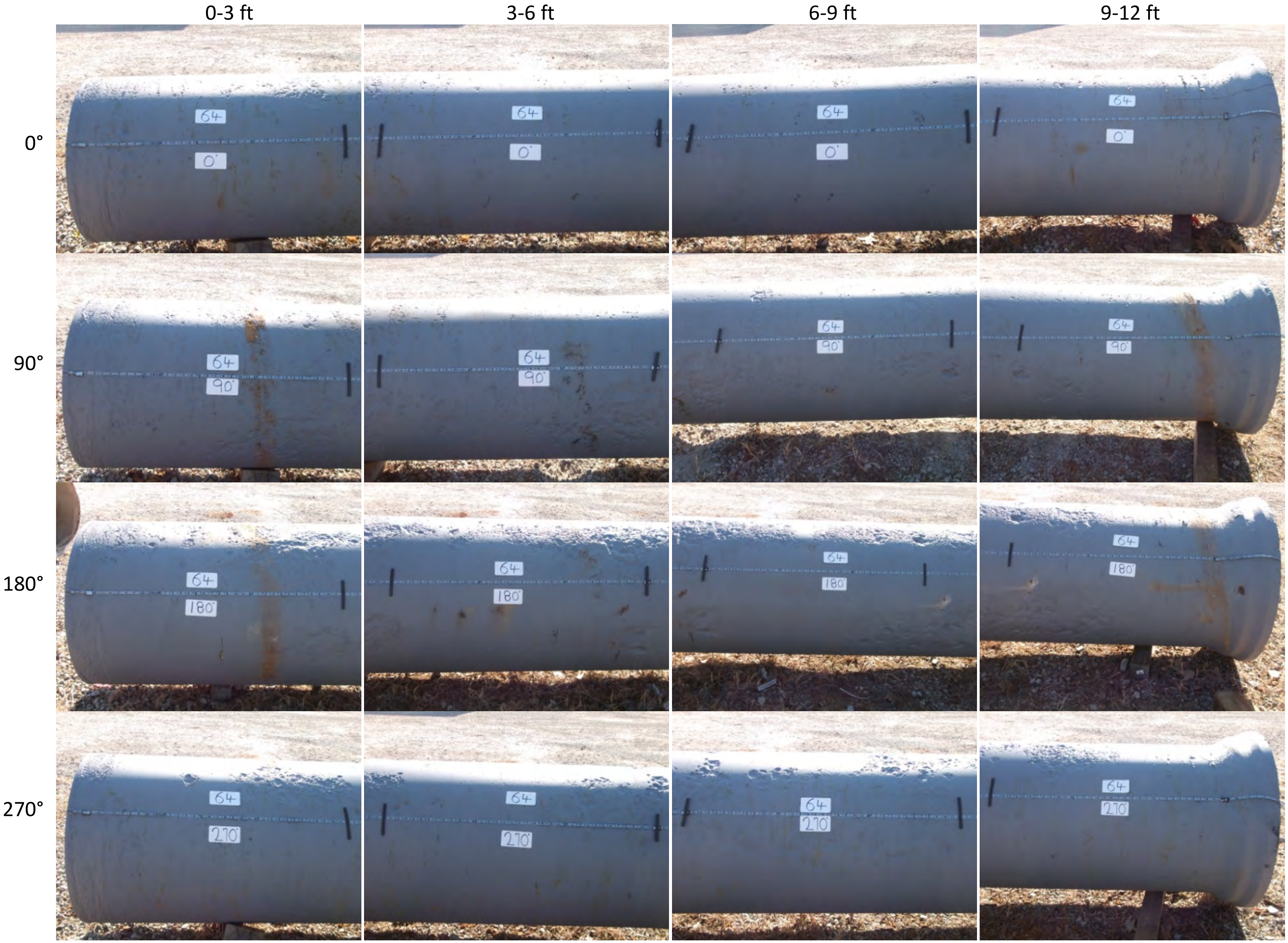


Figure A-64(2).  Pipe 64 after Sandblasting

### Table A-64(1). Wall Thickness of Cast Iron at Spigot with Caliper

| Pipe Number | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| | 10˚ | 130˚ | 290˚ | 330˚ |
| 64 | 0.801 | 0.793 | 0.7965 | 0.797 |

### Table A-64(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)

| Pipe Number | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| | Caliper | UT | | | UT | | | UT | | |
| 64 | 0.782 | 0.776 | 0.765 | 0.766 | 0.797 | 0.776 | 0.774 | 0.796 | 0.815 | x |
| | 0.784 | 0.771 | 0.777 | 0.765 | 0.765 | 0.771 | 0.790 | 0.810 | 0.806 | x |
| | 0.788 | 0.762 | 0.759 | 0.766 | 0.775 | 0.766 | 0.771 | x | x | 0.807 |
| **Average** | 0.785 | 0.767 | | | 0.776 | | | 0.807 | | |
| **Standard Deviation** | 0.003 | 0.006 | | | 0.011 | | | 0.007 | | |
| **Minimum** | 0.782 | 0.759 | | | 0.765 | | | 0.796 | | |
| **Maximum** | 0.788 | 0.777 | | | 0.797 | | | 0.815 | | |
| **Repeat Center Cell** | - | 0.770 | | | 0.760 | | | 0.810 | | |

### Table A-64(3). Outer Diameter Measurement Using a pi Tape

| Pipe Number | Outer Diameter | | |
|---|---|---|---|
| | Spigot | Center | Bell |
| 64 | 25.830 | 25.875 | 25.860 |

### Table A-64(4). Wall Thickness of Cement Liner at Spigot with Caliper

| Measurement (Inches) | 10˚ | 130˚ | 290˚ | 330˚ |
|---|---|---|---|---|
| **Cast Iron** | 0.801 | 0.793 | 0.7965 | 0.797 |
| **Cast Iron & Cement Liner** | 1.096 | 1.098 | 0.952 | 1.078 |
| **Cement Liner** | 0.295 | 0.305 | 0.1555 | 0.281 |

Table A-64(5).  Scanned Pipe 64 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Spigot (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| H11-64 | -7.0 | 128.0 | 0.2878 | 37% | 0.4922 | 63% | 265 | 8:49 |
| H12-64 | 12.2 | 119.1 | 0.2429 | 31% | 0.5371 | 69% | 256 | 8:31 |
| | | 113.1 | 0.2280 | 29% | 0.5520 | 71% | 260 | 8:40 |
| | | 135.5 | 0.2264 | 29% | 0.5536 | 71% | 238 | 7:56 |
| | | 133.1 | 0.1689 | 22% | 0.6111 | 78% | 271 | 9:02 |
| H13-64 | 24.6 | 112.5 | 0.2689 | 34% | 0.5111 | 66% | 127 | 4:14 |
| | | 127.0 | 0.2484 | 32% | 0.5316 | 68% | 109 | 3:38 |
| | | 135.0 | 0.2122 | 27% | 0.5678 | 73% | 145 | 4:50 |
| H14-64 | 8.8 | 142.5 | 0.3287 | 42% | 0.4513 | 58% | 18 | 0:36 |
| | | 117.0 | 0.1358 | 17% | 0.6442 | 83% | 34 | 1:07 |
| H21-64 | 8.8 | 103.3 | 0.2685 | 34% | 0.5115 | 66% | 276 | 9:11 |
| | | 100.9 | 0.1697 | 22% | 0.6103 | 78% | 347 | 11:33 |
| H22-64 | 20.1 | 81.5 | 0.3772 | 48% | 0.4028 | 52% | 245 | 8:09 |
| | | 78.5 | 0.3130 | 40% | 0.4670 | 60% | 189 | 6:18 |
| | | 78.5 | 0.3004 | 39% | 0.4796 | 61% | 247 | 8:13 |
| | | 89.0 | 0.2866 | 37% | 0.4934 | 63% | 240 | 8:00 |
| | | 82.4 | 0.2866 | 37% | 0.4934 | 63% | 265 | 8:49 |
| | | 93.5 | 0.2803 | 36% | 0.4997 | 64% | 247 | 8:13 |
| | | 82.0 | 0.2689 | 34% | 0.5111 | 66% | 236 | 7:51 |
| | | 90.5 | 0.2598 | 33% | 0.5202 | 67% | 245 | 8:09 |
| | | 79.0 | 0.2476 | 32% | 0.5324 | 68% | 265 | 8:49 |
| | | 119.0 | 0.2280 | 29% | 0.5520 | 71% | 260 | 8:40 |
| H23-64 | -11.9 | 78.0 | 0.4138 | 53% | 0.3662 | 47% | 176 | 5:51 |
| | | 112.4 | 0.2681 | 34% | 0.5119 | 66% | 127 | 4:14 |
| | | 90.0 | 0.2331 | 30% | 0.5469 | 70% | 129 | 4:18 |
| | | 86.5 | 0.2173 | 28% | 0.5627 | 72% | 134 | 4:27 |
| H24-64 | 9.6 | | - | - | - | - | | - |
| H31-64 | 1.8 | 120.5 | 0.2118 | 27% | 0.5682 | 73% | 287 | 9:33 |
| | | 47.0 | 0.1555 | 20% | 0.6245 | 80% | 291 | 9:42 |
| H32-64 | 30.4 | 42.5 | 0.5642 | 72% | 0.2158 | 28% | 254 | 8:27 |
| | | 49.0 | 0.3524 | 45% | 0.4276 | 55% | 265 | 8:49 |
| | | 78.8 | 0.3130 | 40% | 0.4670 | 60% | 189 | 6:18 |
| | | 78.8 | 0.3004 | 39% | 0.4796 | 61% | 247 | 8:13 |
| | | 75.5 | 0.2760 | 35% | 0.5040 | 65% | 251 | 8:22 |
| | | 50.0 | 0.2646 | 34% | 0.5154 | 66% | 258 | 8:36 |
| | | 78.9 | 0.2476 | 32% | 0.5324 | 68% | 265 | 8:49 |
| | | 125.0 | 0.2472 | 32% | 0.5328 | 68% | 258 | 8:36 |
| H33-64 | -1.9 | 47.5 | 0.4346 | 56% | 0.3454 | 44% | 182 | 6:04 |
| | | 78.8 | 0.3902 | 50% | 0.3898 | 50% | 178 | 5:56 |
| | | 51.0 | 0.3409 | 44% | 0.4391 | 56% | 169 | 5:38 |

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Spigot (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| | | 42.0 | 0.3193 | 41% | 0.4607 | 59% | 167 | 5:34 |
| | | 44.0 | 0.3134 | 40% | 0.4666 | 60% | 180 | 6:00 |
| | | 48.5 | 0.2354 | 30% | 0.5446 | 70% | 171 | 5:42 |
| H34-64 | 15.8 | 71.0 | 0.1197 | 15% | 0.6603 | 85% | 31 | 1:02 |
| H41-64 | -7.9 | 42.8 | 0.1520 | 19% | 0.6280 | 81% | 278 | 9:15 |
| H42-64 | 51.8 | 42.8 | 0.5642 | 72% | 0.2158 | 28% | 254 | 8:27 |
| | | 37.5 | 0.4142 | 53% | 0.3658 | 47% | 187 | 6:13 |
| | | 39.0 | 0.3508 | 45% | 0.4292 | 55% | 198 | 6:36 |
| | | 27.0 | 0.3220 | 41% | 0.4580 | 59% | 189 | 6:18 |
| | | 39.5 | 0.3035 | 39% | 0.4765 | 61% | 187 | 6:13 |
| | | 34.5 | 0.2929 | 38% | 0.4871 | 62% | 245 | 8:09 |
| | | 36.0 | 0.2909 | 37% | 0.4891 | 63% | 249 | 8:18 |
| | | 28.0 | 0.2567 | 33% | 0.5233 | 67% | 183 | 6:06 |
| | | 32.5 | 0.2535 | 33% | 0.5265 | 68% | 240 | 8:00 |
| H43-64 | 27.3 | 37.5 | 0.4390 | 56% | 0.3410 | 44% | 182 | 6:04 |
| | | 29.0 | 0.3902 | 50% | 0.3898 | 50% | 178 | 5:56 |
| | | 33.0 | 0.3028 | 39% | 0.4772 | 61% | 165 | 5:29 |
| | | 30.5 | 0.3008 | 39% | 0.4792 | 61% | 171 | 5:42 |
| | | 42.8 | 0.2980 | 38% | 0.4820 | 62% | 165 | 5:29 |
| | | 39.0 | 0.2811 | 36% | 0.4989 | 64% | 176 | 5:51 |
| H44-64 | 25.5 | 33.0 | 0.1508 | 19% | 0.6292 | 81% | 45 | 1:29 |

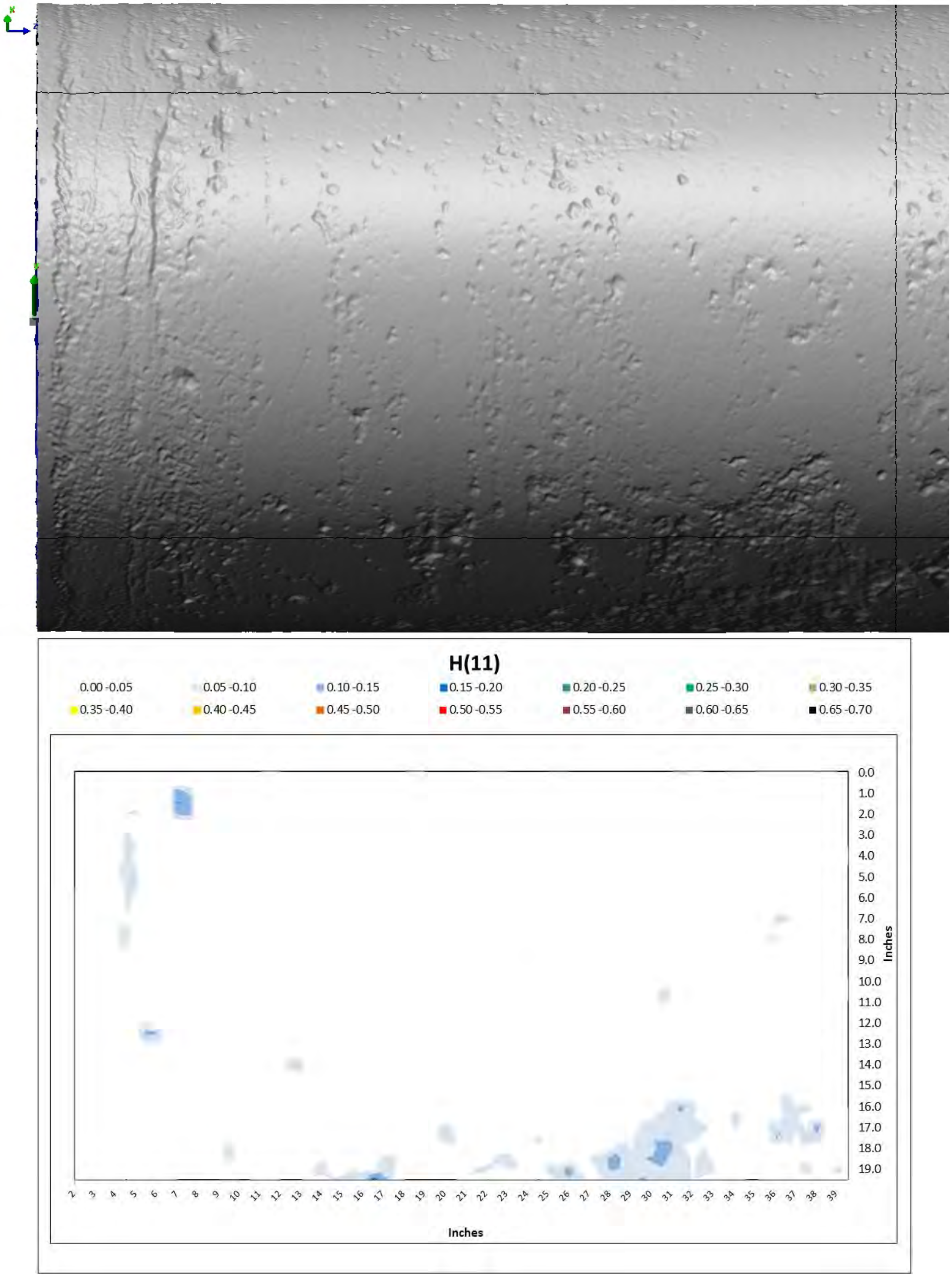


Figure A-64(1). Pipe 64, 0-3 feet and 0-90 degrees

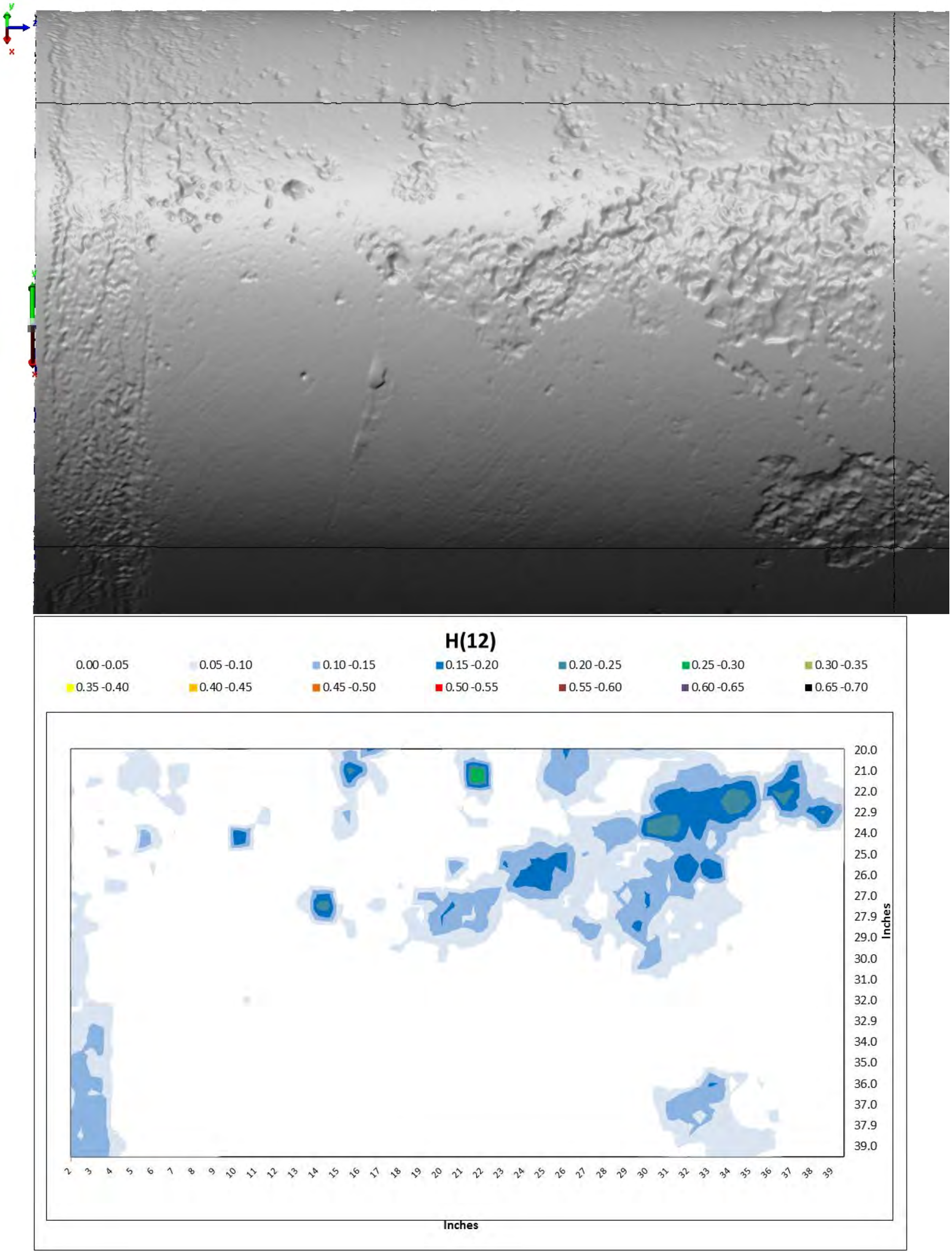


Figure A-64(2). Pipe 64, 0-3 feet and 90-180 degrees

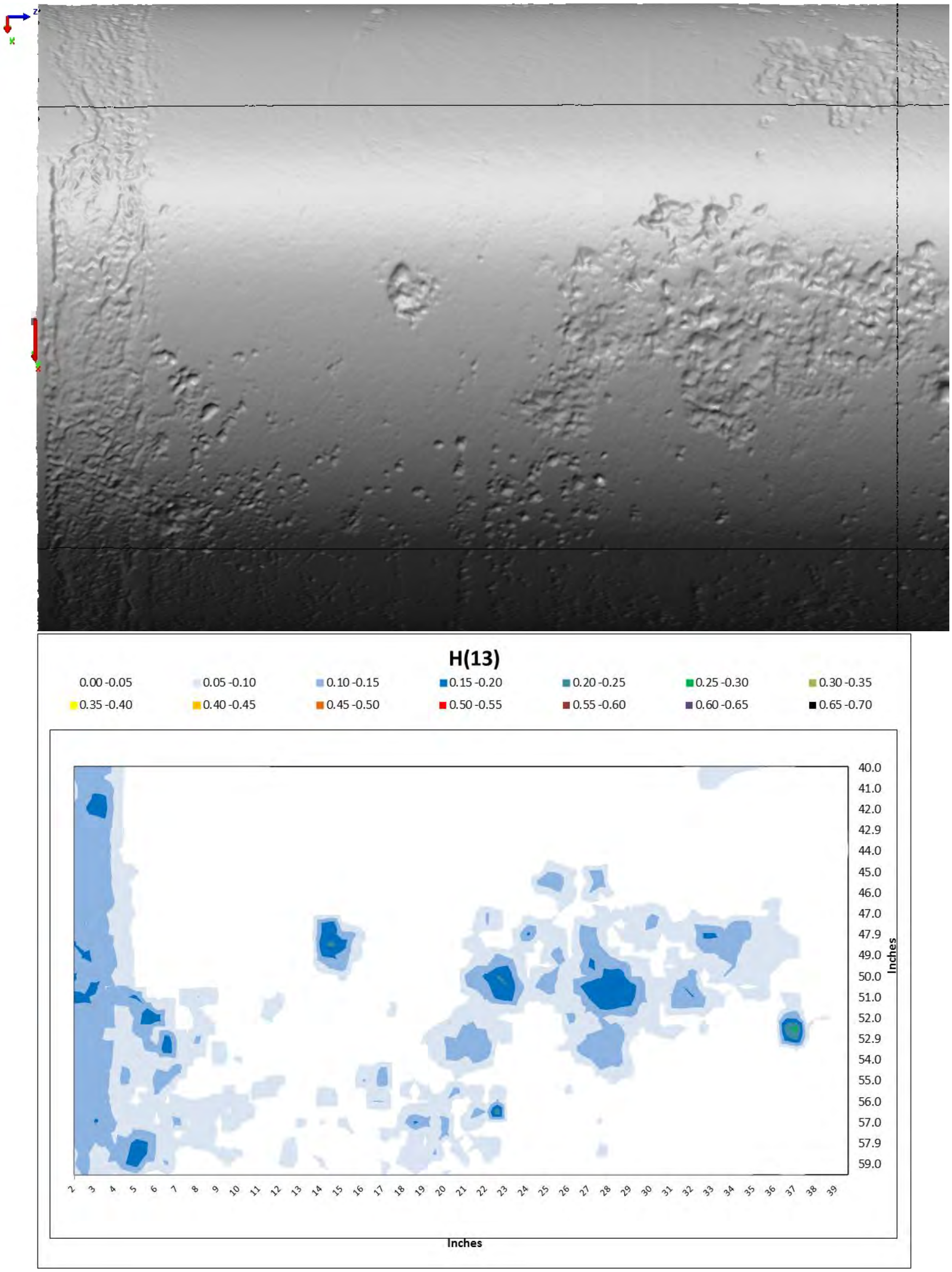


Figure A-64(3). Pipe 64, 0-3 feet and 180-270 degrees

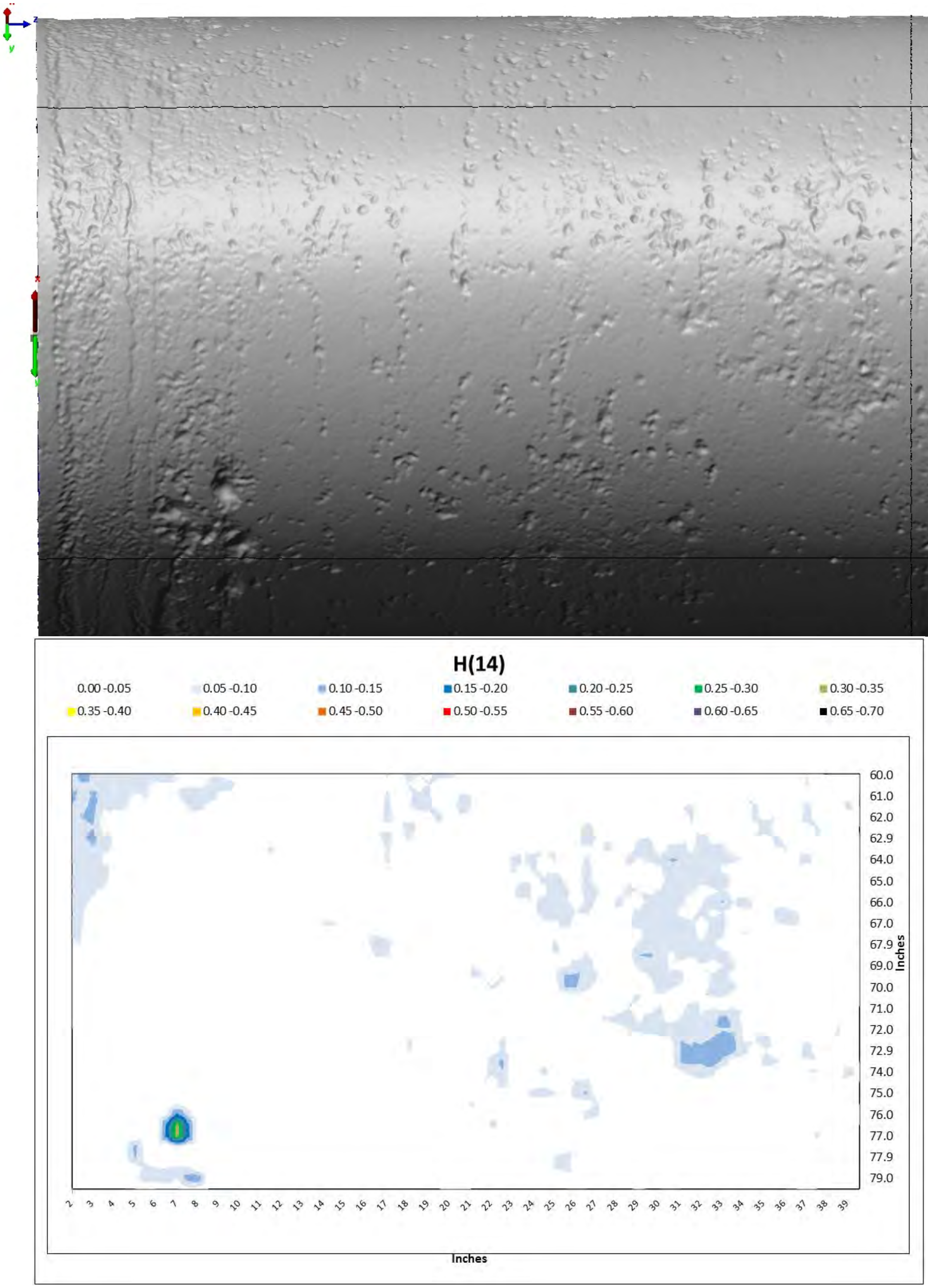


**Figure A-64(4). Pipe 64, 0-3 feet and 270-300 degrees**

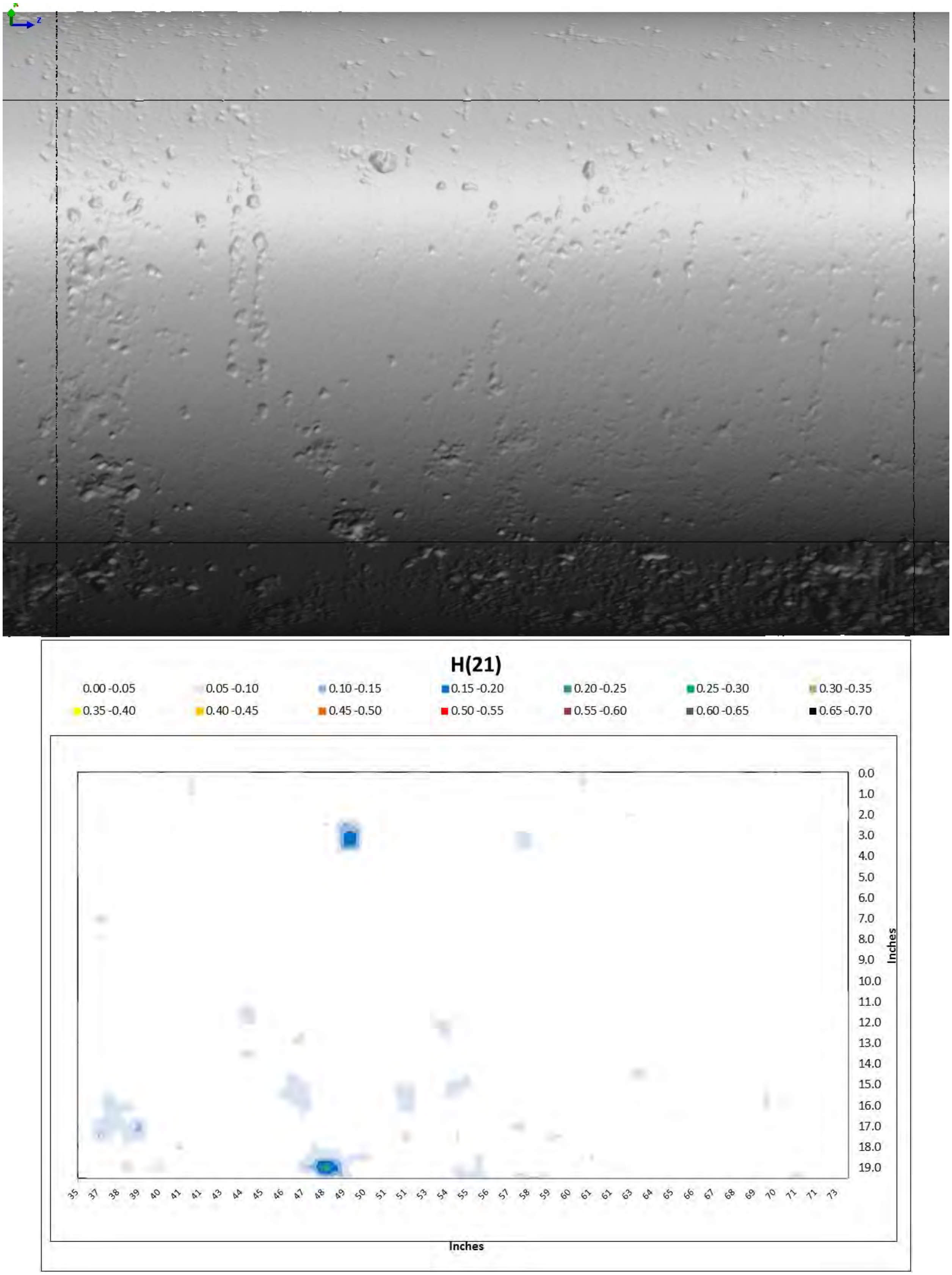


Figure A-64(5). Pipe 64, 3-6 feet and 0-90 degrees

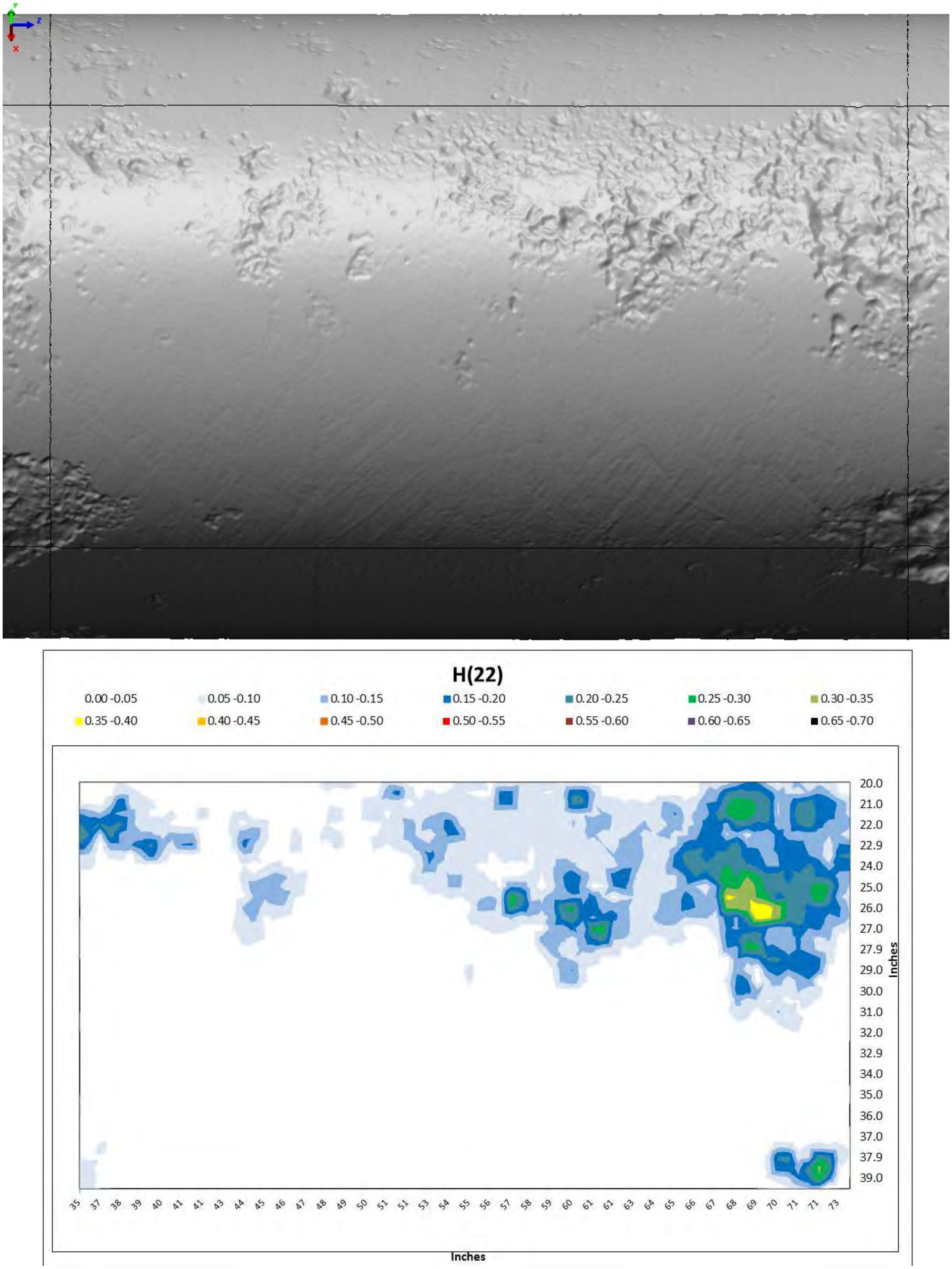


**Figure A-64(6). Pipe 64, 3-6 feet and 90-180 degrees**

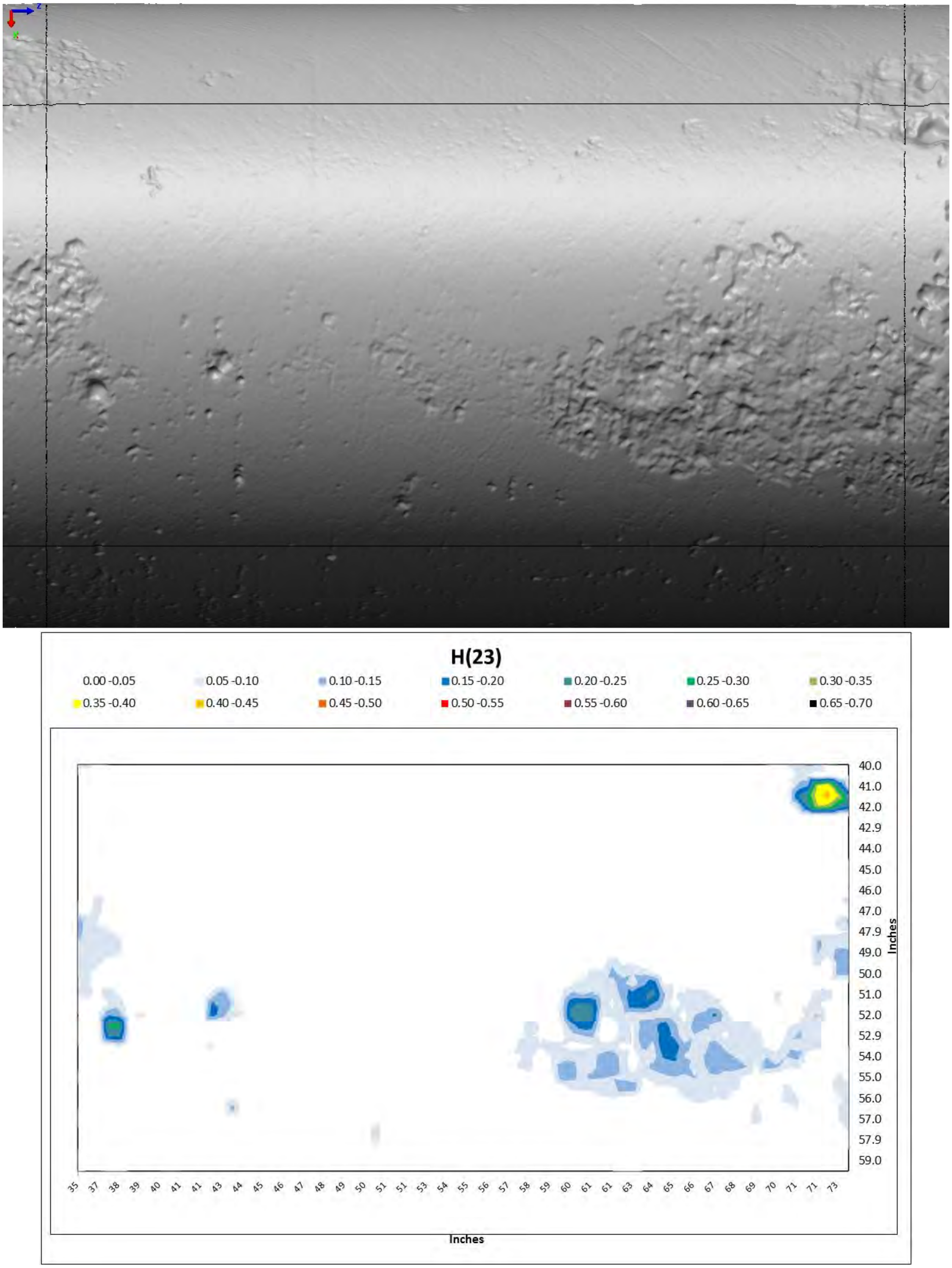


Figure A-64(7). Pipe 64, 3-6 feet and 180-270 degrees

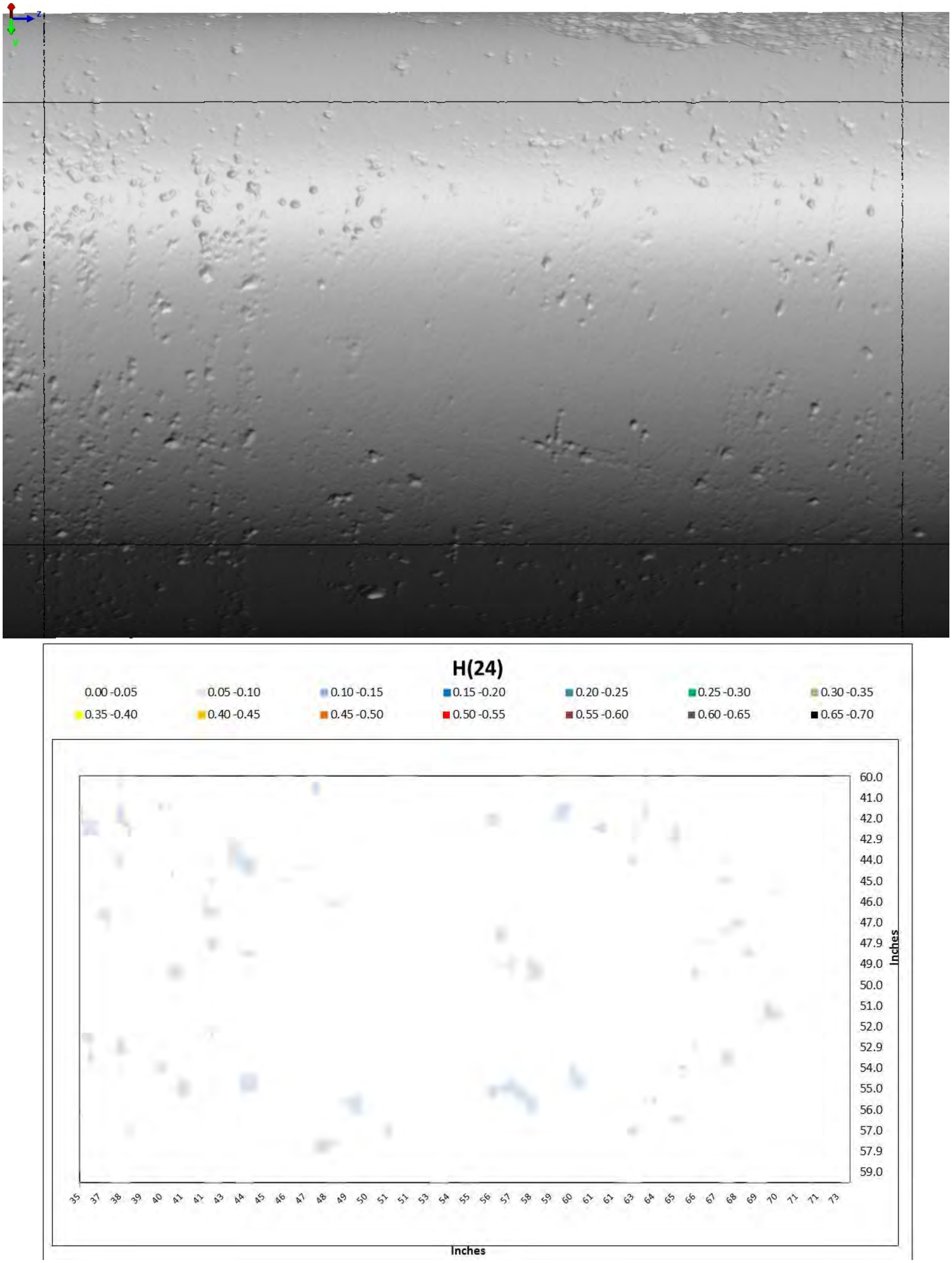


**Figure A-64(8). Pipe 64, 3-6 feet and 270-300 degrees**

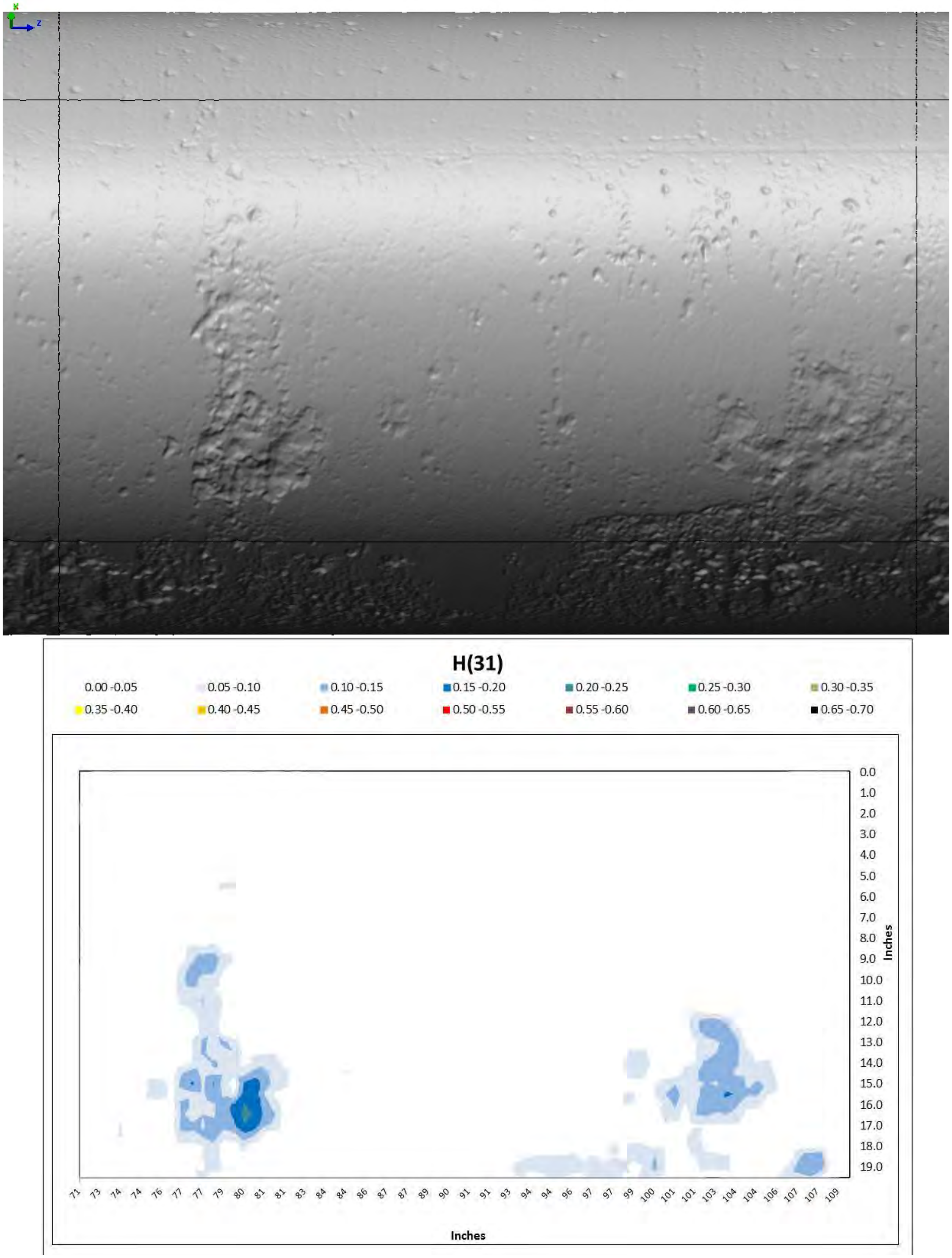


**Figure A-64(9). Pipe 64, 6-9 feet and 0-90 degrees**

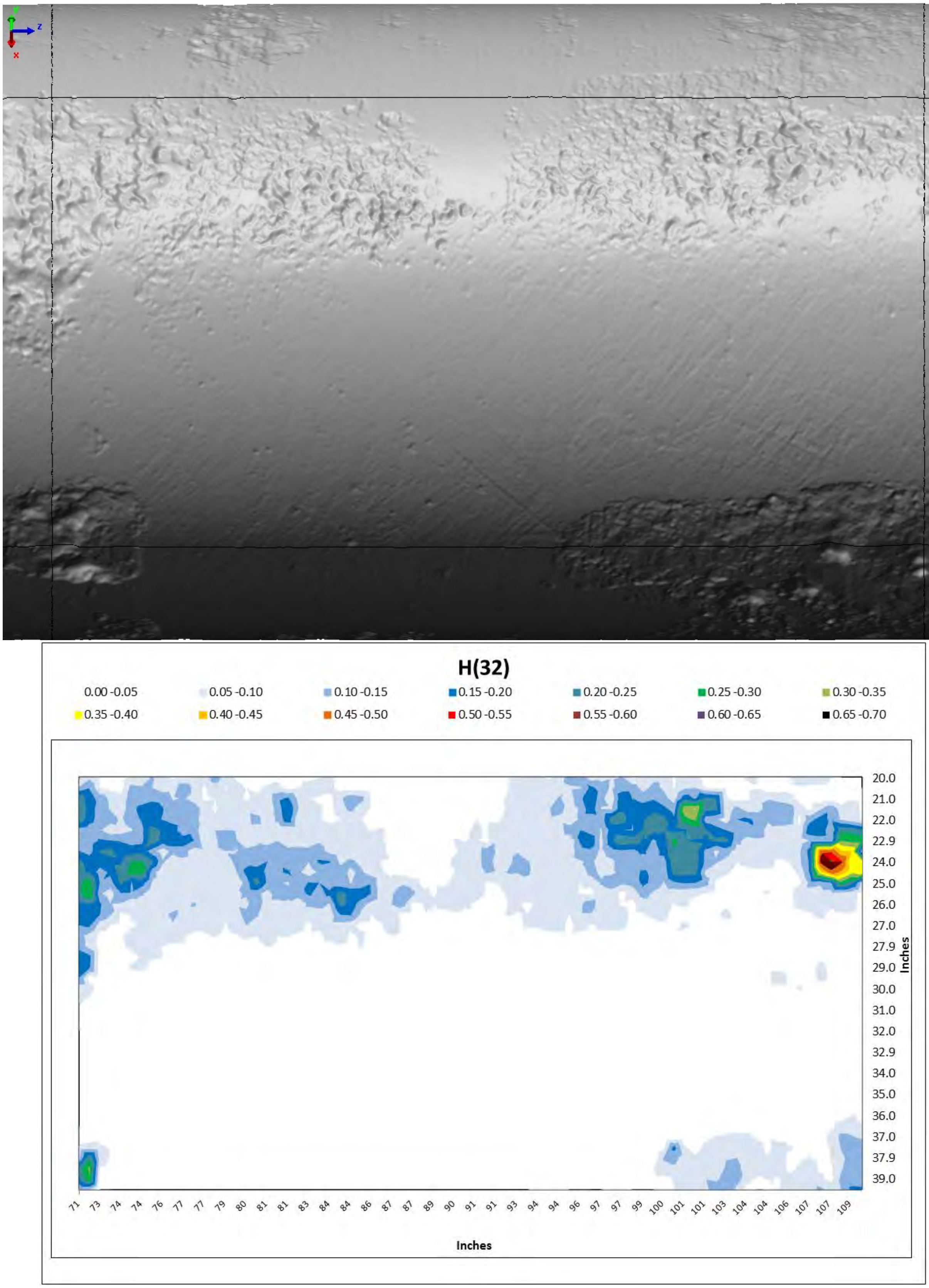


**Figure A-64(10). Pipe 64, 6-9 feet and 90-180 degrees**

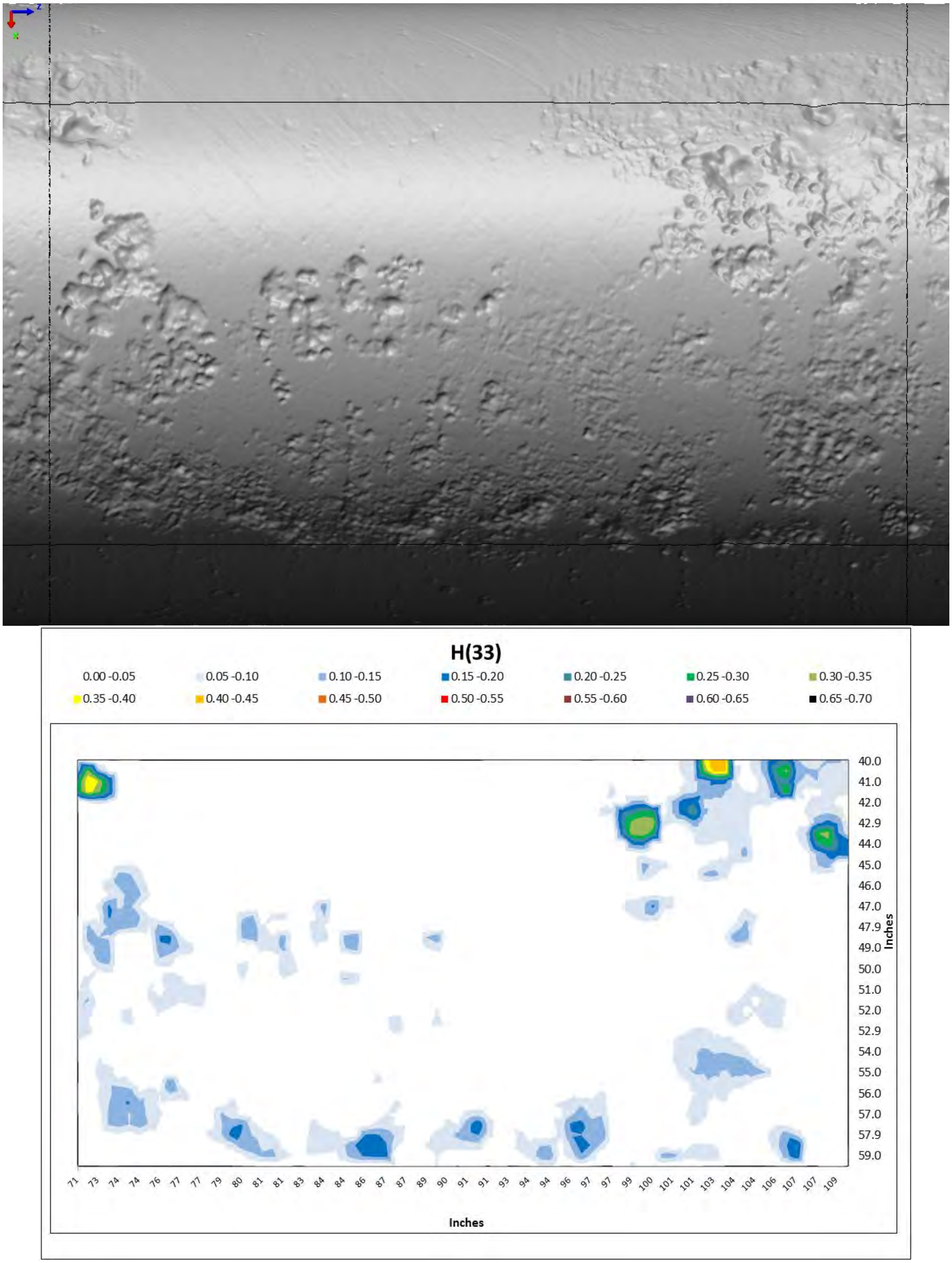


Figure A-64(11). Pipe 64, 6-9 feet and 180-270 degrees

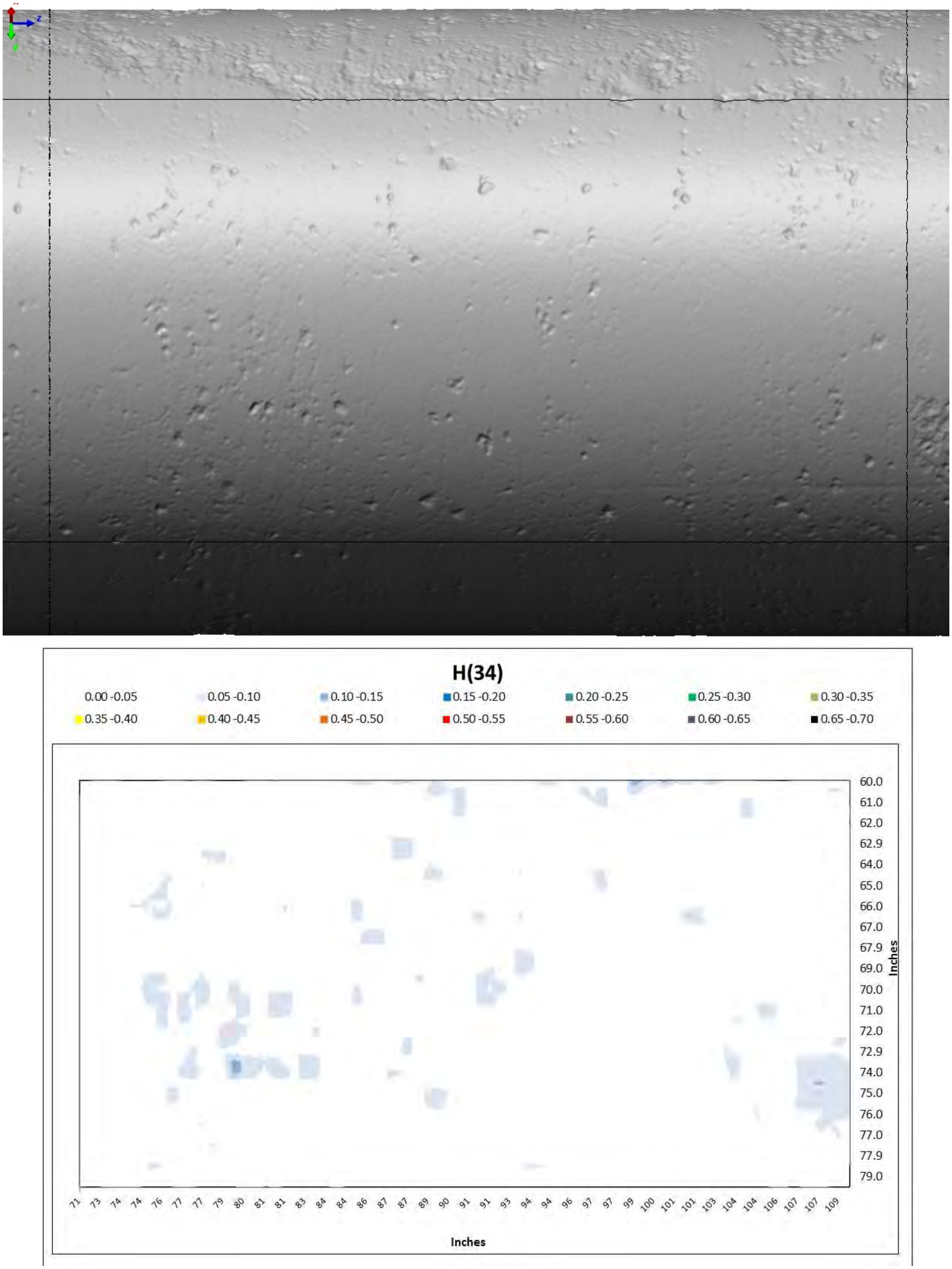


Figure A-64(12). Pipe 64, 6-9 feet and 270-300 degrees

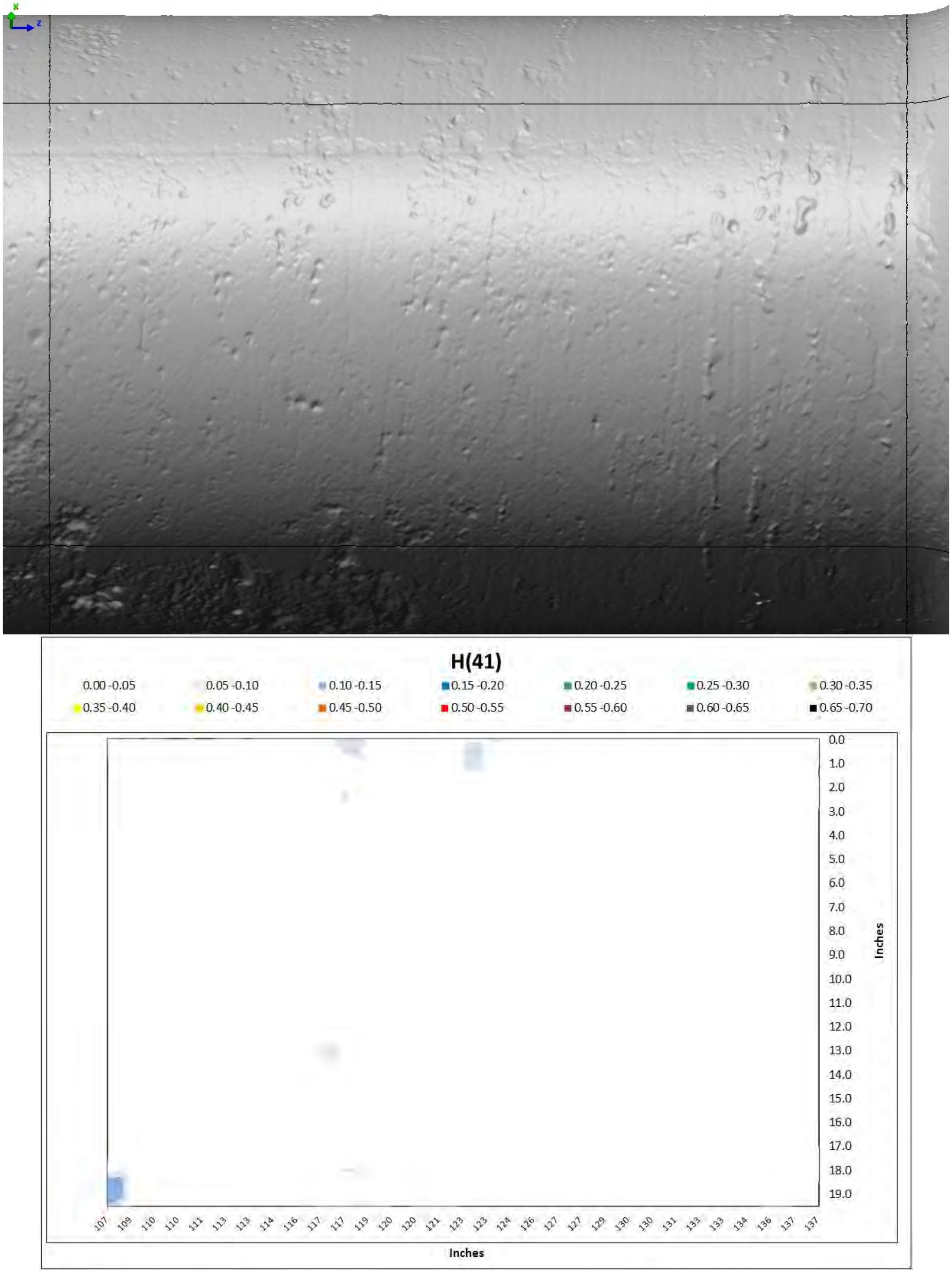


Figure A-64(13). Pipe 64, 9-12 feet and 0-90 degrees

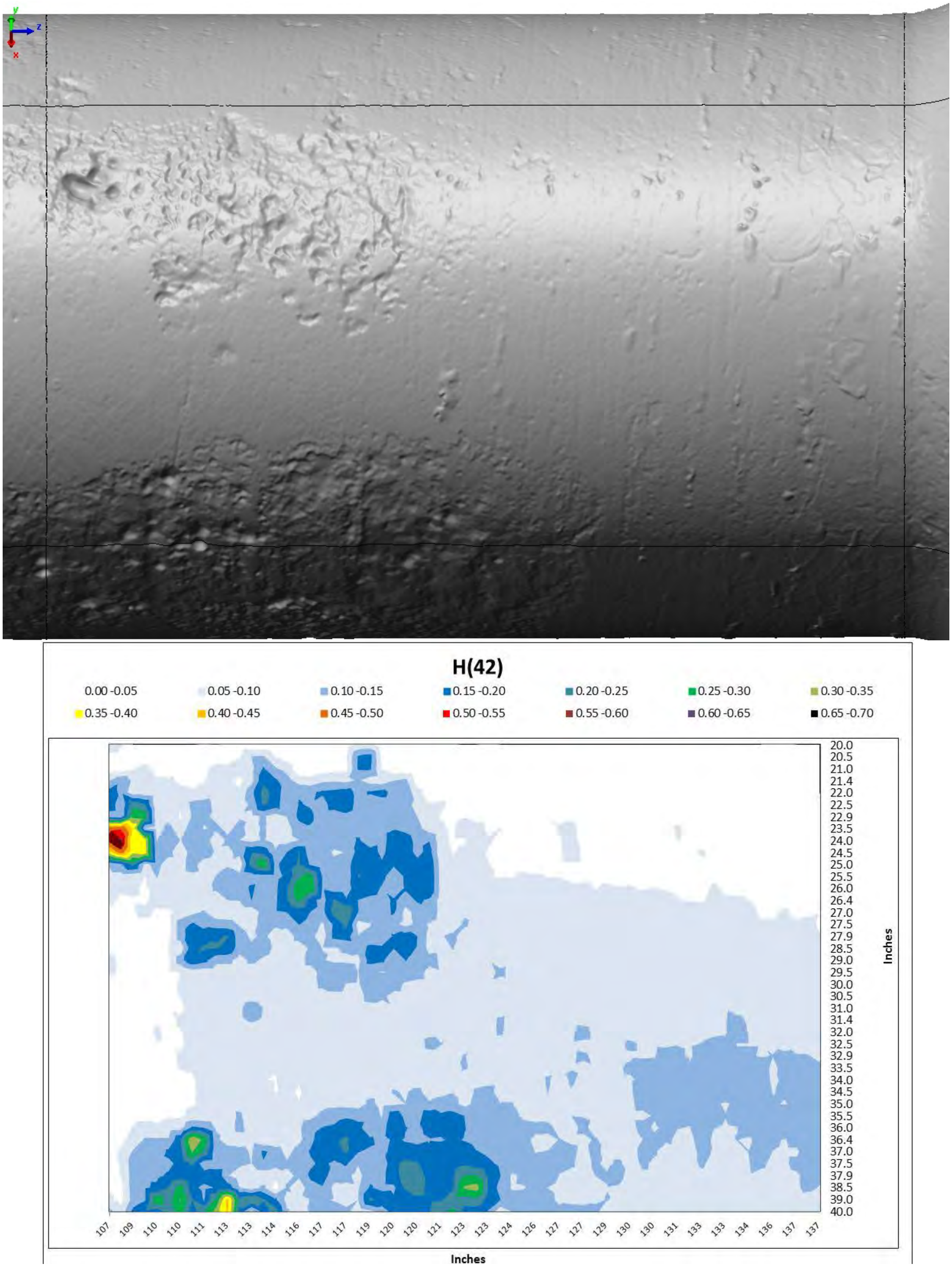


Figure A-64(14). Pipe 64, 9-12 feet and 90-180 degrees

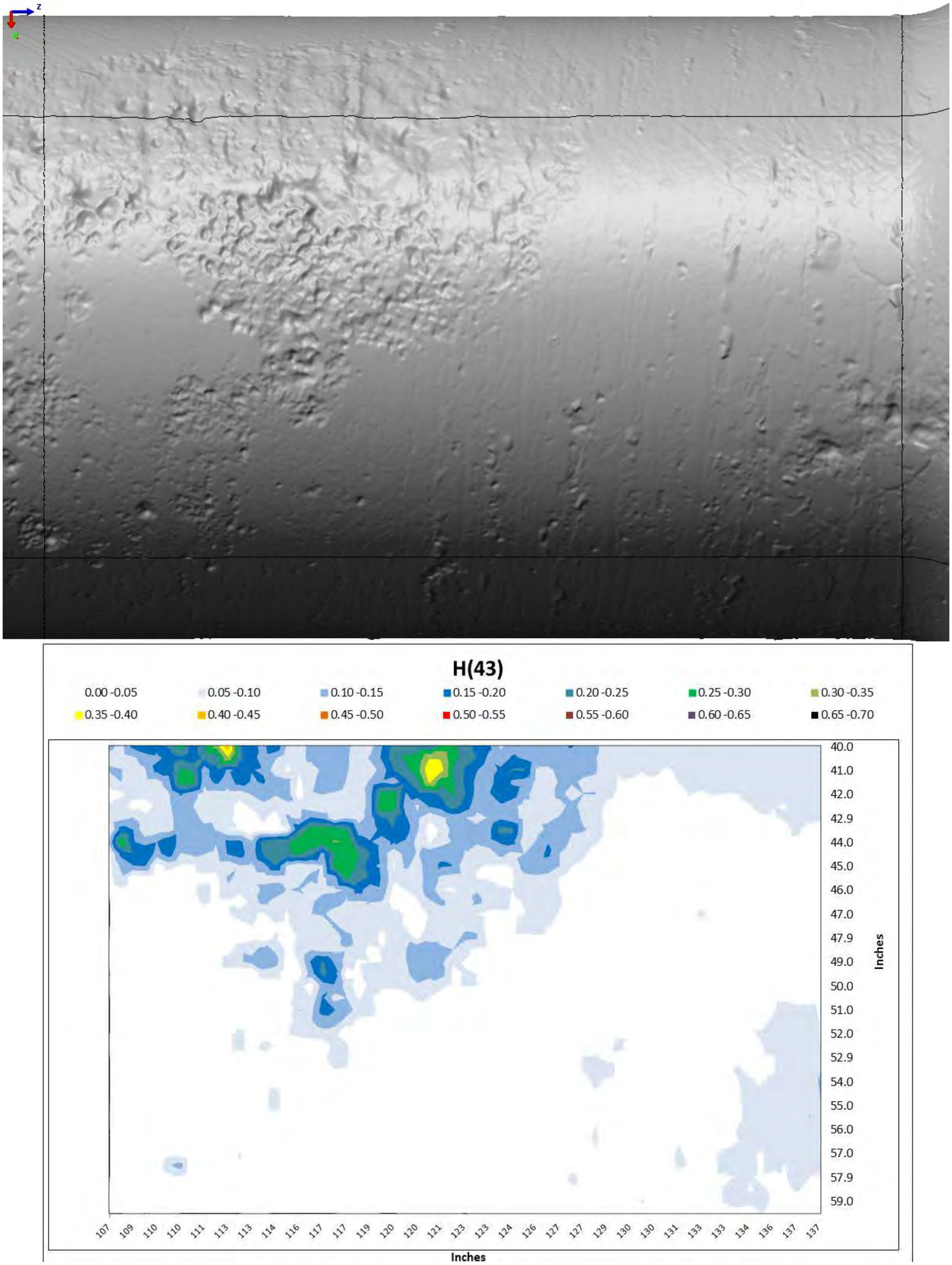


**Figure A-64(15). Pipe 64, 9-12 feet and 180-270 degrees**

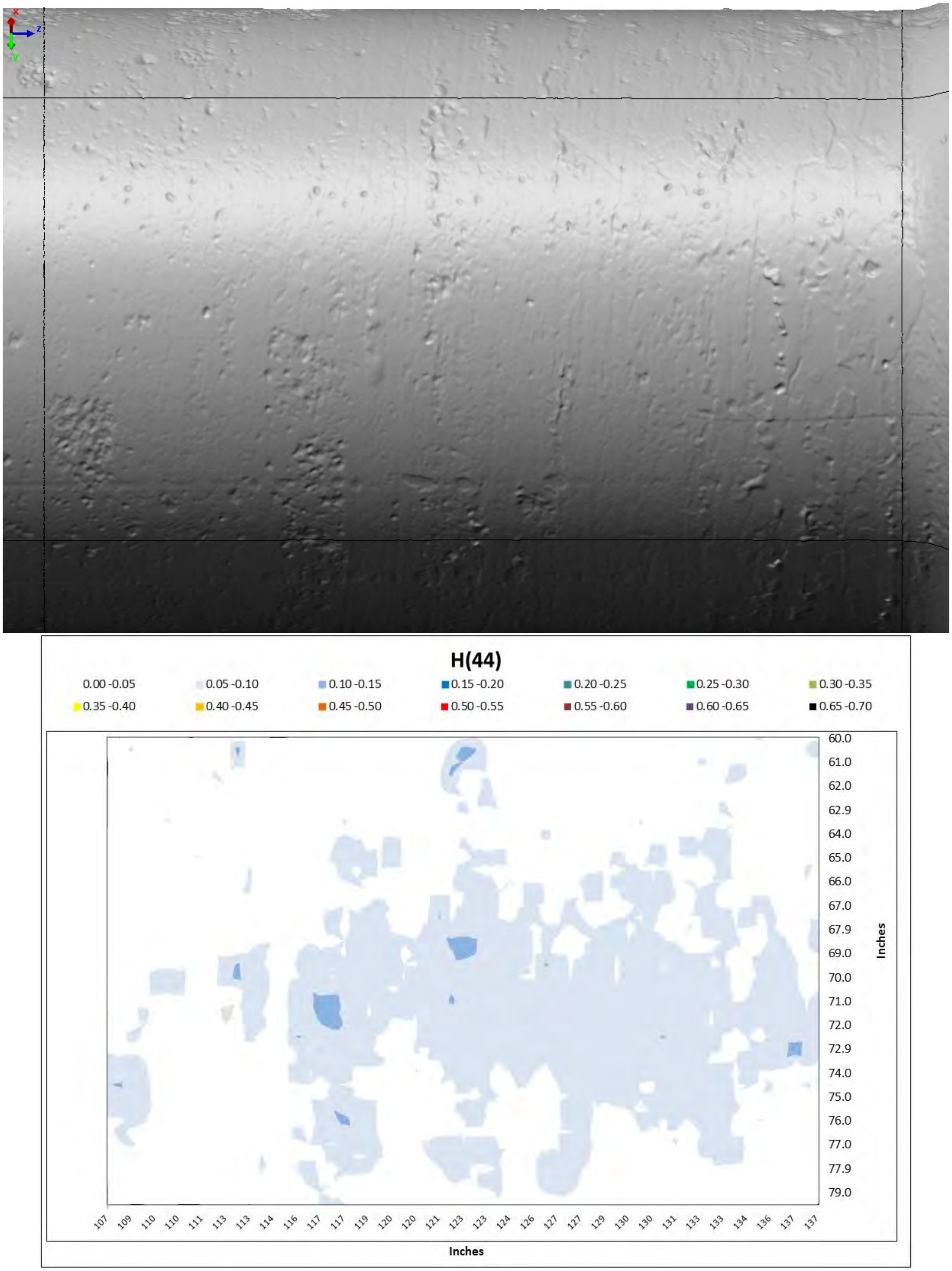


**Figure A-64(16). Pipe 64, 9-12 feet and 270-300 degrees**

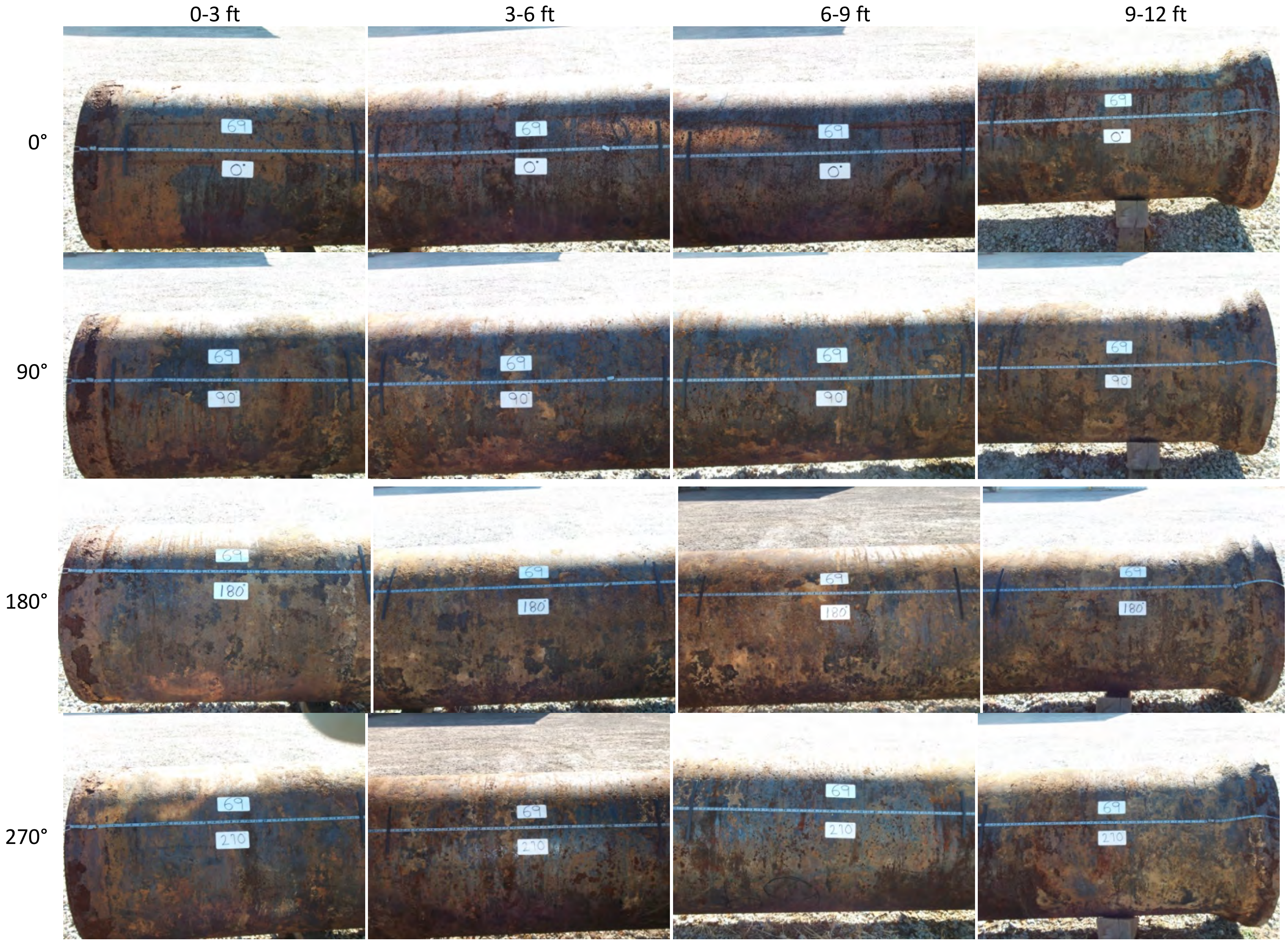


Figure A-69(1). Pipe 69 as Removed from Site

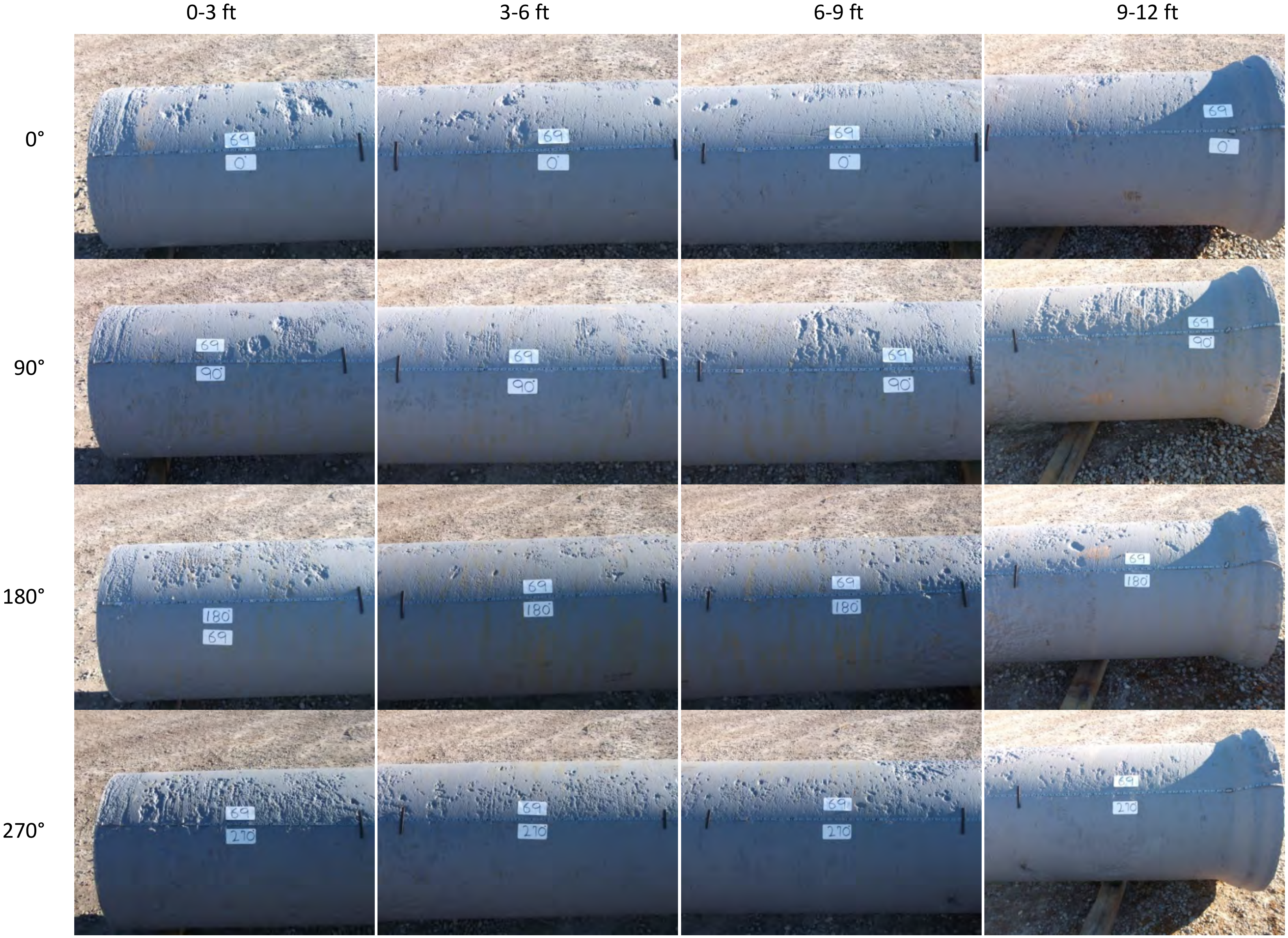


Figure A-69(2). Pipe 69 after Sandblasting

**Table A-69(1). Wall Thickness of Cast Iron at Spigot with Caliper**

| | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| Pipe Number | 70° | 110° | 200° | 315° |
| 69 | 0.776 | 0.774 | 0.742 | 0.742 |

**Table A-69(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)**

| | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| Pipe Number | Caliper | UT | | | UT | | | UT | | |
| 69 | 0.756 | 0.792 | 0.768 | 0.758 | 0.730 | 0.736 | 0.739 | 0.783 | 0.780 | 0.786 |
| | 0.752 | 0.767 | 0.755 | 0.744 | 0.730 | 0.755 | 0.730 | 0.778 | 0.788 | 0.776 |
| | 0.750 | 0.796 | 0.760 | 0.760 | 0.728 | 0.739 | 0.734 | 0.814 | 0.784 | 0.776 |
| **Average** | 0.753 | 0.767 | | | 0.736 | | | 0.785 | | |
| **Standard Deviation** | 0.003 | 0.017 | | | 0.008 | | | 0.012 | | |
| **Minimum** | 0.750 | 0.744 | | | 0.728 | | | 0.776 | | |
| **Maximum** | 0.756 | 0.796 | | | 0.755 | | | 0.814 | | |
| **Repeat Center Cell** | - | 0.759 | | | 0.740 | | | 0.808 | | |

**Table A-69(3). Outer Diameter Measurement Using a pi Tape**

| | Outer Diameter | | |
|---|---|---|---|
| Pipe Number | Spigot | Center | Bell |
| 69 | 25.880 | 25.810 | 25.860 |

**Table A-69(4). Wall Thickness of Cement Liner at Spigot with Caliper**

| Measurement (Inches) | 70° | 110° | 200° | 315° |
|---|---|---|---|---|
| **Cast Iron** | 0.776 | 0.774 | 0.742 | 0.742 |
| **Cast Iron & Cement Liner** | 0.958 | 0.980 | 0.998 | 0.998 |
| **Cement Liner** | 0.182 | 0.206 | 0.256 | 0.256 |

## Table A-69(5). Pipe 69 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Bell (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| 069-095-129-027-109 | 38.1 | 48.5 | 0.362 | 46% | 0.42 | 54% | 200 | 6:40 |
| | | 47.0 | 0.351 | 45% | 0.43 | 55% | 207 | 6:54 |
| | | 44.0 | 0.320 | 41% | 0.46 | 59% | 202 | 6:44 |
| 069-083-030-014-078 | 11.4 | 61.0 | 0.391 | 50% | 0.39 | 50% | 321 | 10:42 |
| | | 63.0 | 0.239 | 31% | 0.54 | 69% | 317 | 10:34 |
| | | 63.0 | 0.238 | 30% | 0.54 | 70% | 272 | 9:04 |
| | | 65.0 | 0.233 | 30% | 0.55 | 70% | 308 | 10:16 |
| | | 62.0 | 0.219 | 28% | 0.56 | 72% | 303 | 10:06 |
| 069-106-040-032-089 | 39.5 | 22.0 | 0.584 | 75% | 0.20 | 25% | 307 | 10:14 |
| | | 17.5 | 0.354 | 45% | 0.43 | 55% | 284 | 9:28 |
| | | 33.0 | 0.307 | 39% | 0.47 | 61% | 231 | 7:42 |
| | | 30.5 | 0.272 | 35% | 0.51 | 65% | 291 | 9:42 |
| 069-069-315-010-023 | 1.3 | 80.0 | 0.294 | 38% | 0.49 | 62% | 34 | 1:08 |
| | | 76.0 | 0.251 | 32% | 0.53 | 68% | 38 | 1:16 |
| 069-048-297-006-037 | 1.8 | 100.5 | 0.362 | 46% | 0.42 | 54% | 36 | 1:12 |
| | | 98.0 | 0.173 | 22% | 0.61 | 78% | 59 | 1:58 |
| 069-024-274-014-277 | 17.2 | 123.0 | 0.420 | 54% | 0.36 | 46% | 46 | 1:32 |
| | | 123.5 | 0.365 | 47% | 0.42 | 53% | 68 | 2:16 |
| | | 120.0 | 0.353 | 45% | 0.43 | 55% | 24 | 0:48 |
| | | 123.5 | 0.269 | 34% | 0.51 | 66% | 26 | 0:52 |
| | | 118.0 | 0.239 | 31% | 0.54 | 69% | 82 | 2:44 |
| 069-115-275-014-098 | 11.4 | 26.0 | 0.392 | 50% | 0.39 | 50% | 43 | 1:26 |
| | | 29.0 | 0.241 | 31% | 0.54 | 69% | 358 | 11:56 |
| 069-006-141-015-148 | 30.0 | 131.0 | 0.368 | 47% | 0.41 | 53% | 115 | 3:50 |
| | | 141.0 | 0.367 | 47% | 0.41 | 53% | 117 | 3:54 |
| | | 135.0 | 0.338 | 43% | 0.44 | 57% | 99 | 3:18 |
| | | 138.0 | 0.332 | 43% | 0.45 | 58% | 135 | 4:30 |
| | | 138.0 | 0.327 | 42% | 0.45 | 58% | 84 | 2:48 |
| | | 132.0 | 0.319 | 41% | 0.46 | 59% | 137 | 4:34 |

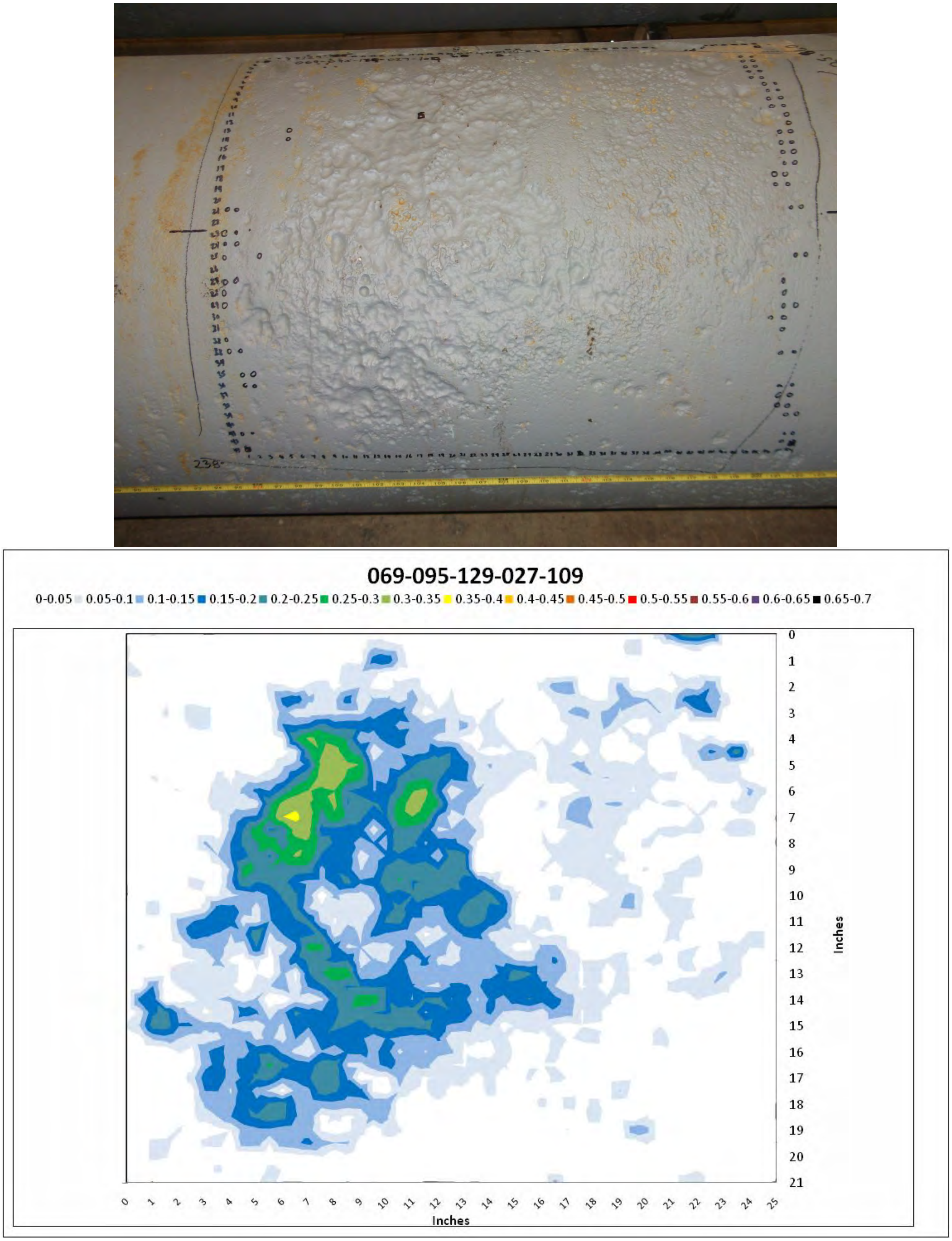


Figure A-69(1). Pipe 69, area 069-095-129-027-109

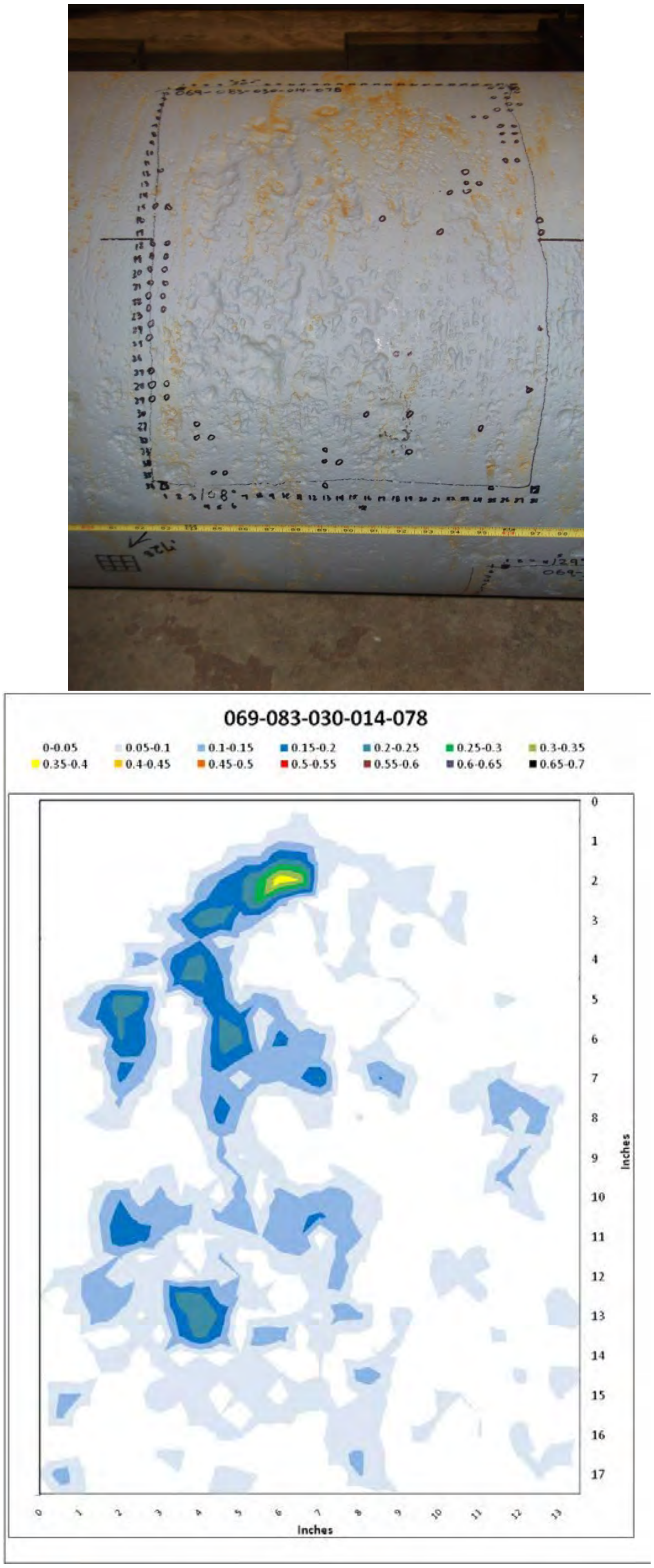


Figure A-69(2). Pipe 69, area 069-083-030-014-078

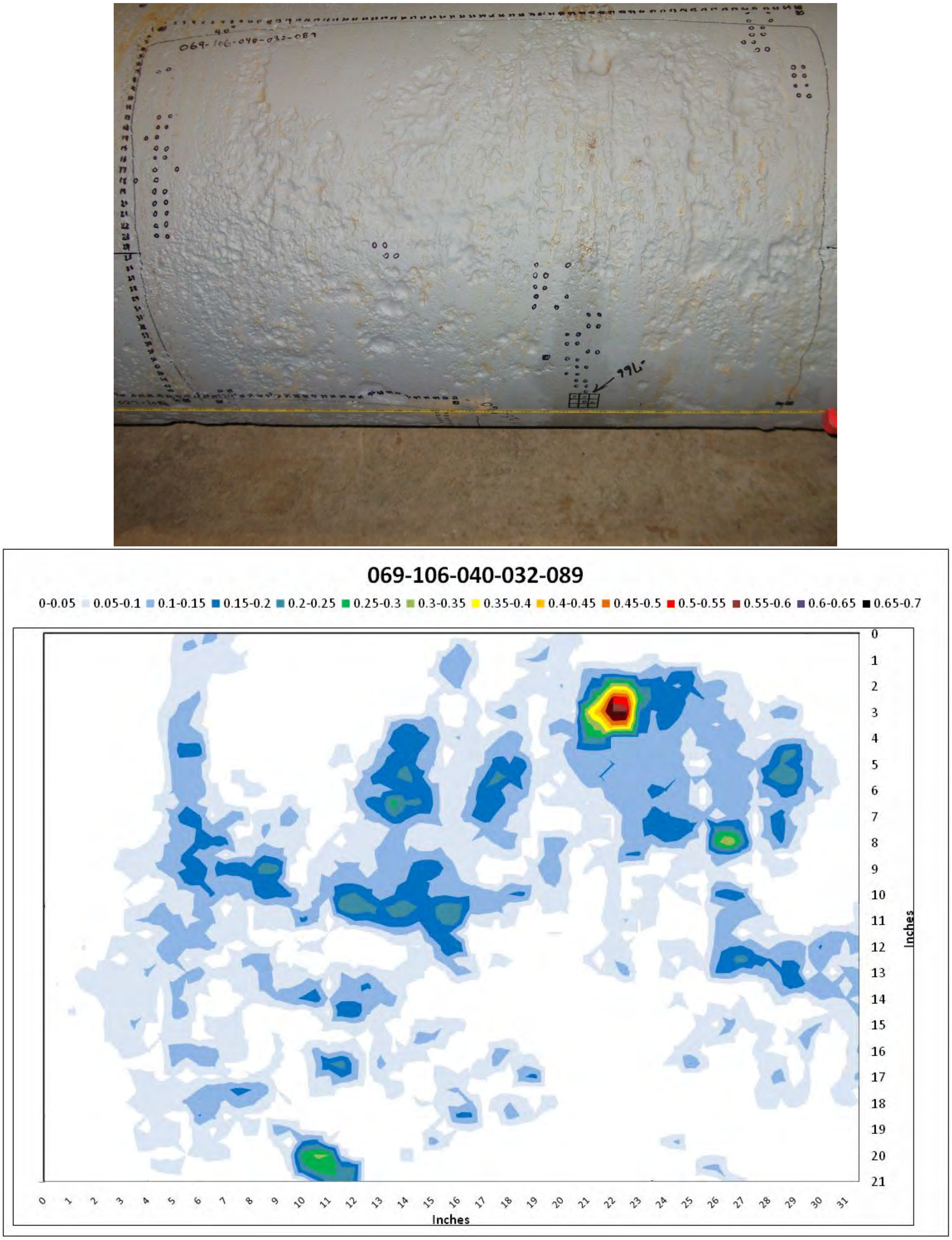


Figure A-69(3). Pipe 69, area 069-106-040-032-089

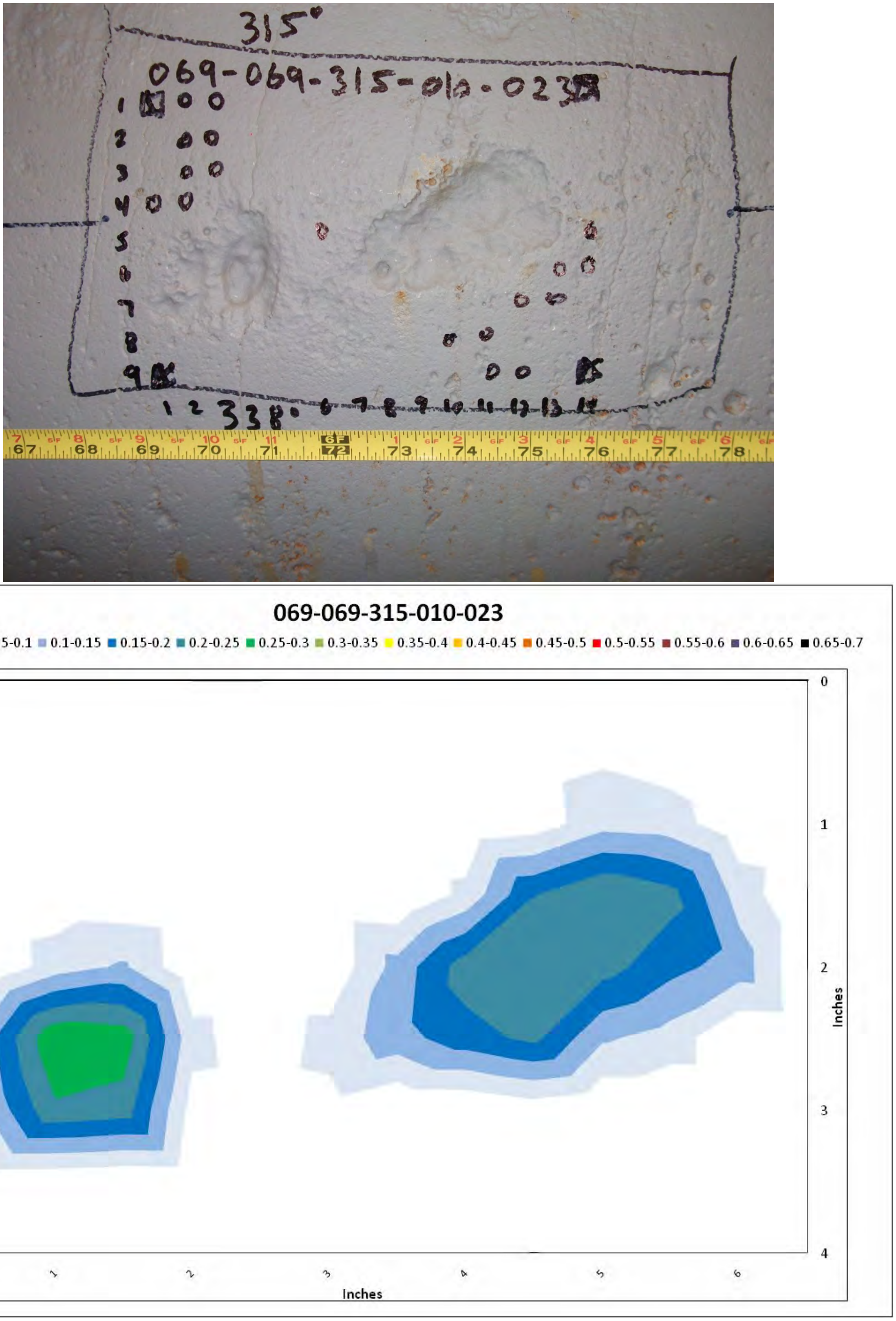


Figure A-69(4). Pipe 69, area 069-069-315-010-023

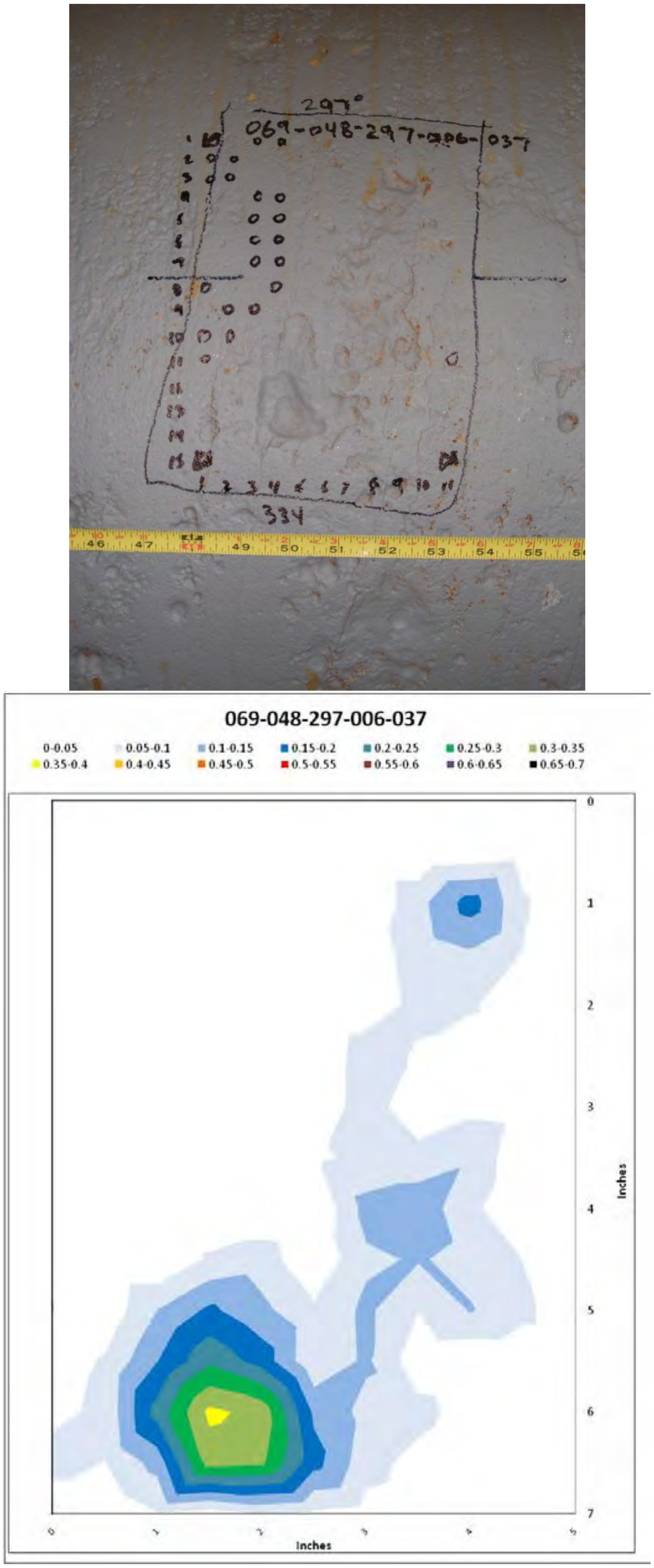


**Figure A-69(5). Pipe 69, area 069-048-297-006-037**

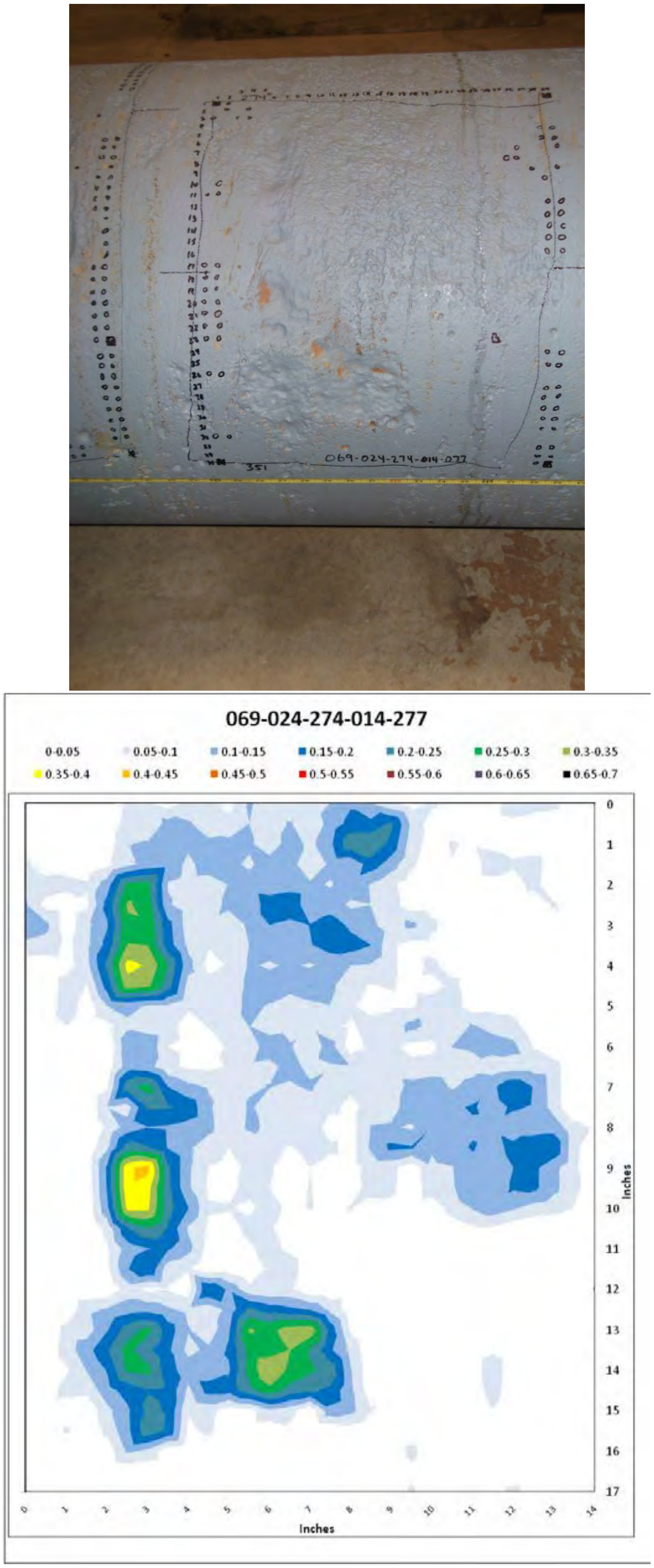


**Figure A-69(6). Pipe 69, area 069-024-274-014-277**

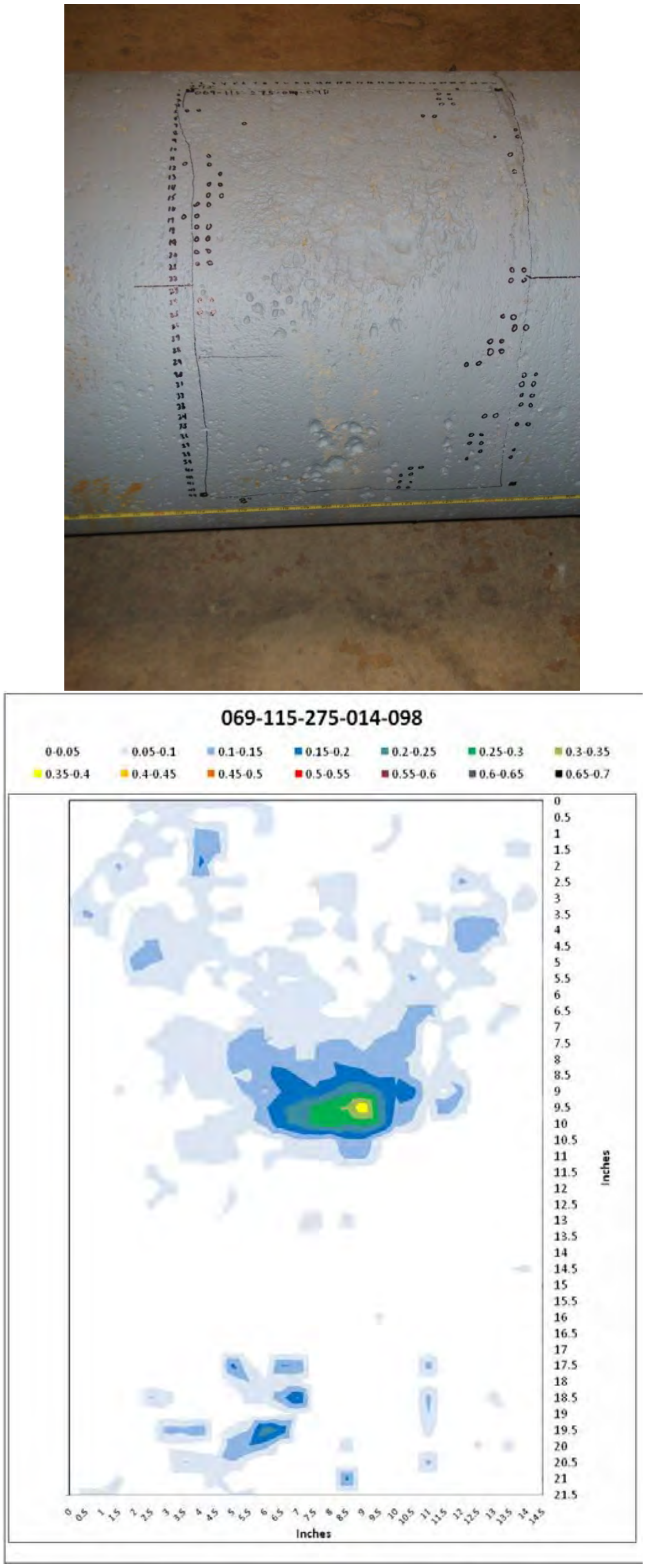


Figure A-69(7). Pipe 69, area 069-115-275-014-098

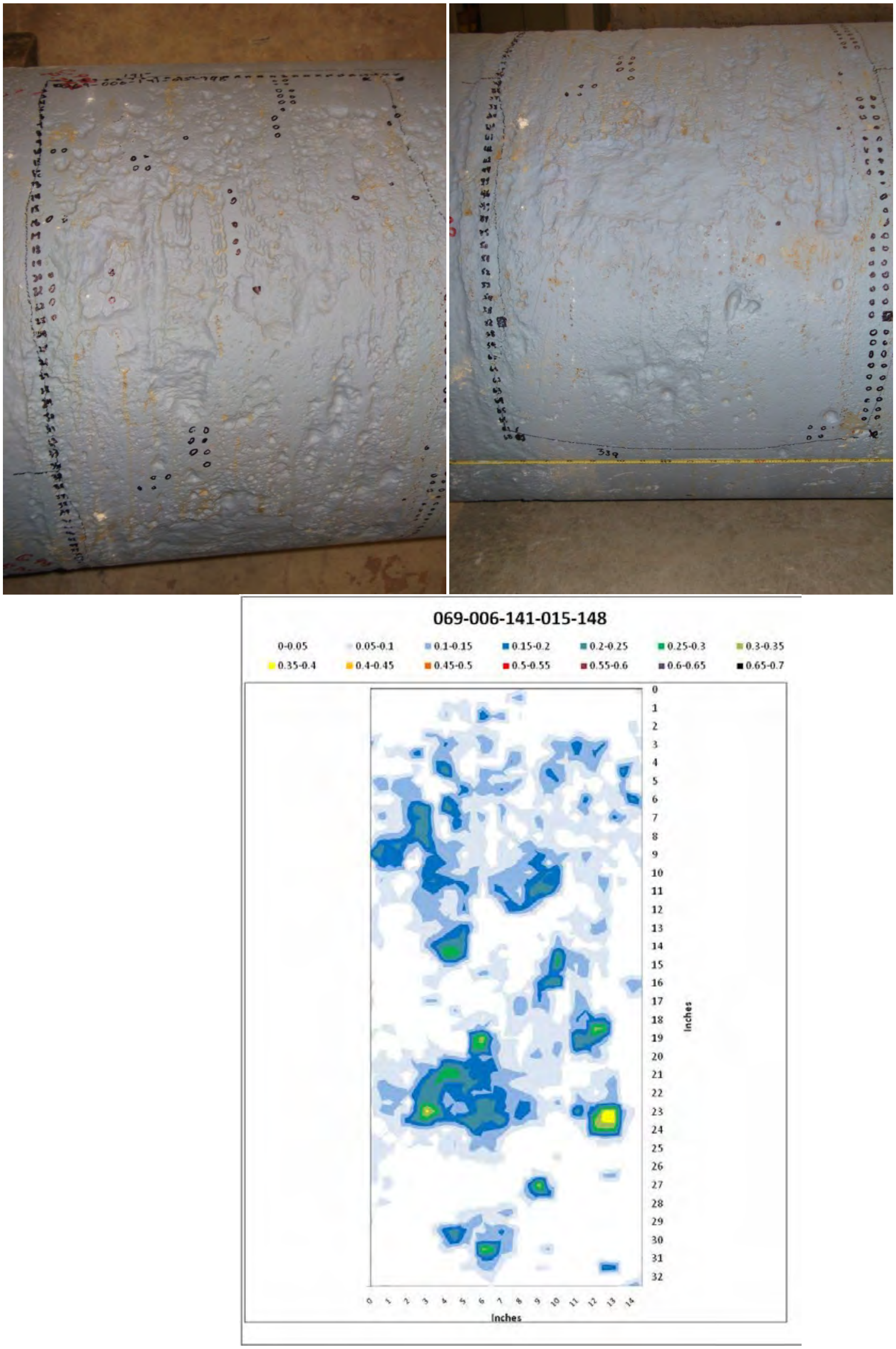


Figure A-69(8). Pipe 69, area 069-006-141-015-148

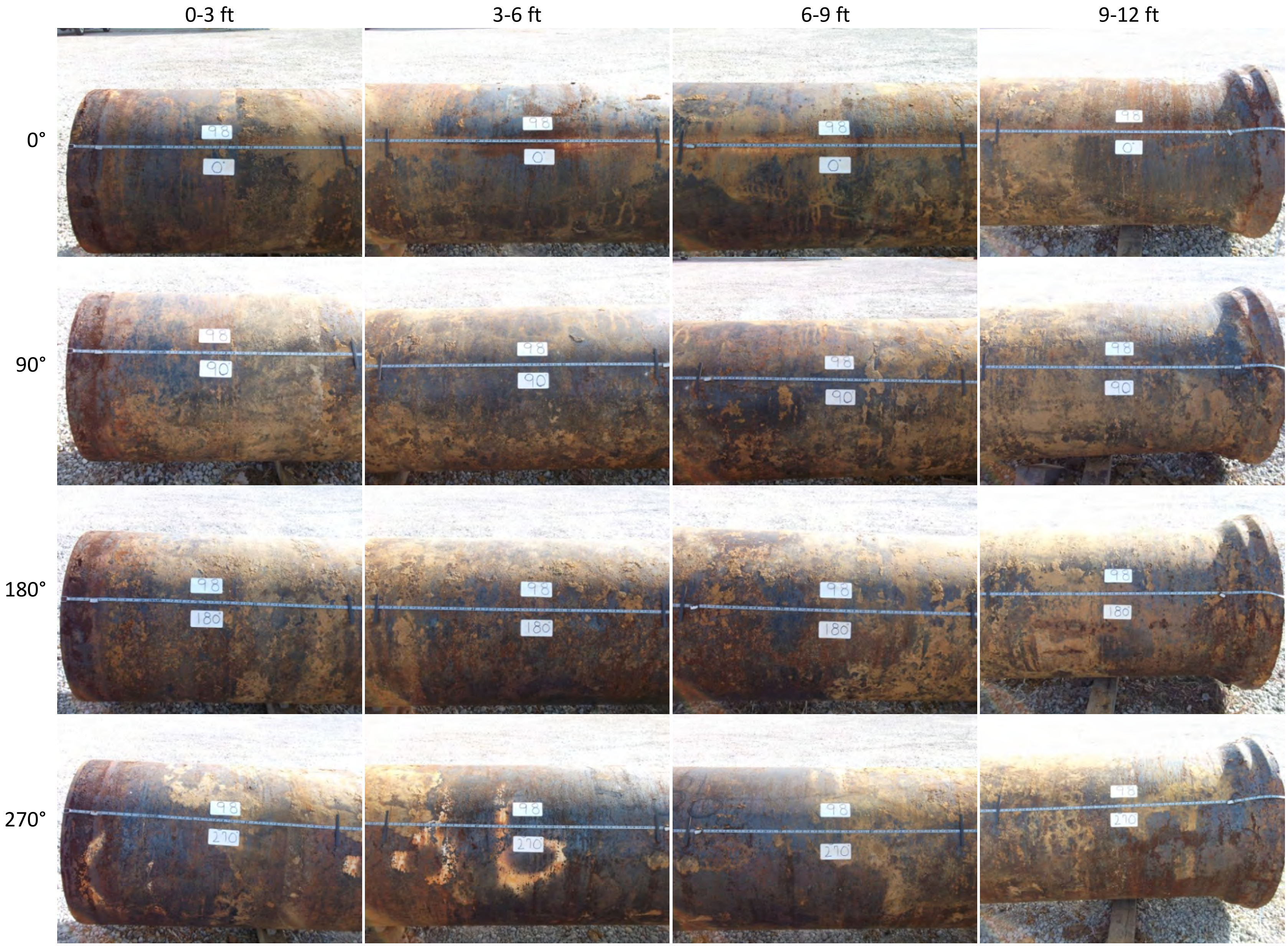


Figure A-98(1). Pipe 98 as Removed from Site

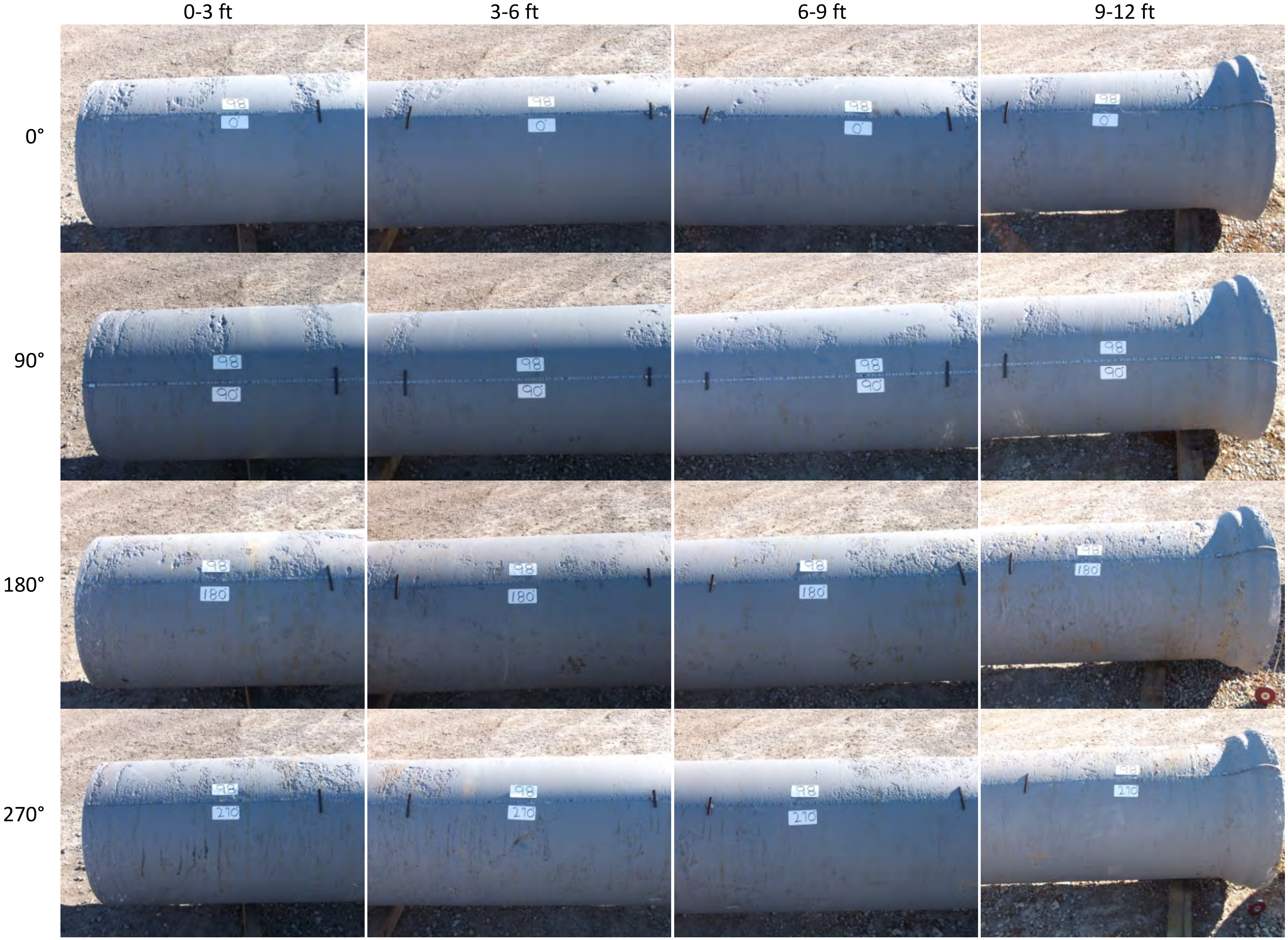


Figure A-98(2). Pipe 98 after Sandblasting

### Table A-98(1). Wall Thickness of Cast Iron at Spigot with Caliper

| Pipe Number | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| | 90° | 180° | 270° | 345° |
| 98 | 0.814 | 0.799 | 0.812 | 0.840 |

### Table A-98(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)

| Pipe Number | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| | Caliper | UT | | | UT | | | UT | | |
| 98 | 0.831 | 0.832 | 0.828 | 0.829 | 0.789 | 0.783 | 0.801 | 0.814 | 0.817 | 0.829 |
| | 0.832 | 0.822 | 0.826 | 0.822 | 0.790 | 0.793 | 0.797 | 0.815 | 0.816 | 0.815 |
| | 0.830 | 0.827 | 0.825 | 0.818 | 0.778 | 0.793 | 0.789 | 0.815 | 0.822 | 0.826 |
| **Average** | 0.831 | 0.825 | | | 0.790 | | | 0.819 | | |
| **Standard Deviation** | 0.001 | 0.004 | | | 0.007 | | | 0.006 | | |
| **Minimum** | 0.830 | 0.818 | | | 0.778 | | | 0.814 | | |
| **Maximum** | 0.832 | 0.832 | | | 0.801 | | | 0.829 | | |
| **Repeat Center Cell** | - | 0.820 | | | 0.796 | | | 0.817 | | |

### Table A-98(3). Outer Diameter Measurement Using a pi Tape

| Pipe Number | Outer Diameter | | |
|---|---|---|---|
| | Spigot | Center | Bell |
| 98 | 25.875 | 25.800 | 25.760 |

### Table A-98(4). Wall Thickness of Cement Liner at Spigot with Caliper

| Measurement (Inches) | 90° | 180° | 270° | 345° |
|---|---|---|---|---|
| **Cast Iron** | 0.814 | 0.799 | 0.812 | 0.840 |
| **Cast Iron & Cement Liner** | 1.102 | 1.11 | 1.085 | 1.078 |
| **Cement Liner** | 0.288 | 0.311 | 0.273 | 0.238 |

### Table A-98(5). Pipe 98 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Bell (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| 098-047-271-012-047 | 5.0 | 96.5 | 0.493 | 63% | 0.29 | 37% | 69 | 2:18 |
| 098-066-282-024-066 | 13.4 | 62.0 | 0.379 | 49% | 0.40 | 51% | 23 | 0:46 |
| | | 81.0 | 0.339 | 43% | 0.44 | 57% | 54 | 1:48 |
| 098-109-337-010-121 | 39.5 | 36.5 | 0.299 | 38% | 0.48 | 62% | 1 | 0:02 |
| | | 39.5 | 0.252 | 32% | 0.53 | 68% | 288 | 9:36 |
| | | 38.5 | 0.236 | 30% | 0.54 | 70% | 310 | 10:20 |
| 098-103-168-029-039 | 24.4 | 21.0 | 0.328 | 42% | 0.45 | 58% | 174 | 5:48 |
| | | 25.0 | 0.314 | 40% | 0.47 | 60% | 163 | 5:26 |
| | | 23.0 | 0.298 | 38% | 0.48 | 62% | 172 | 5:44 |
| | | 36.0 | 0.295 | 38% | 0.49 | 62% | 163 | 5:26 |
| | | 44.0 | 0.251 | 32% | 0.53 | 68% | 176 | 5:52 |
| | | 32.0 | 0.224 | 29% | 0.56 | 71% | 161 | 5:22 |

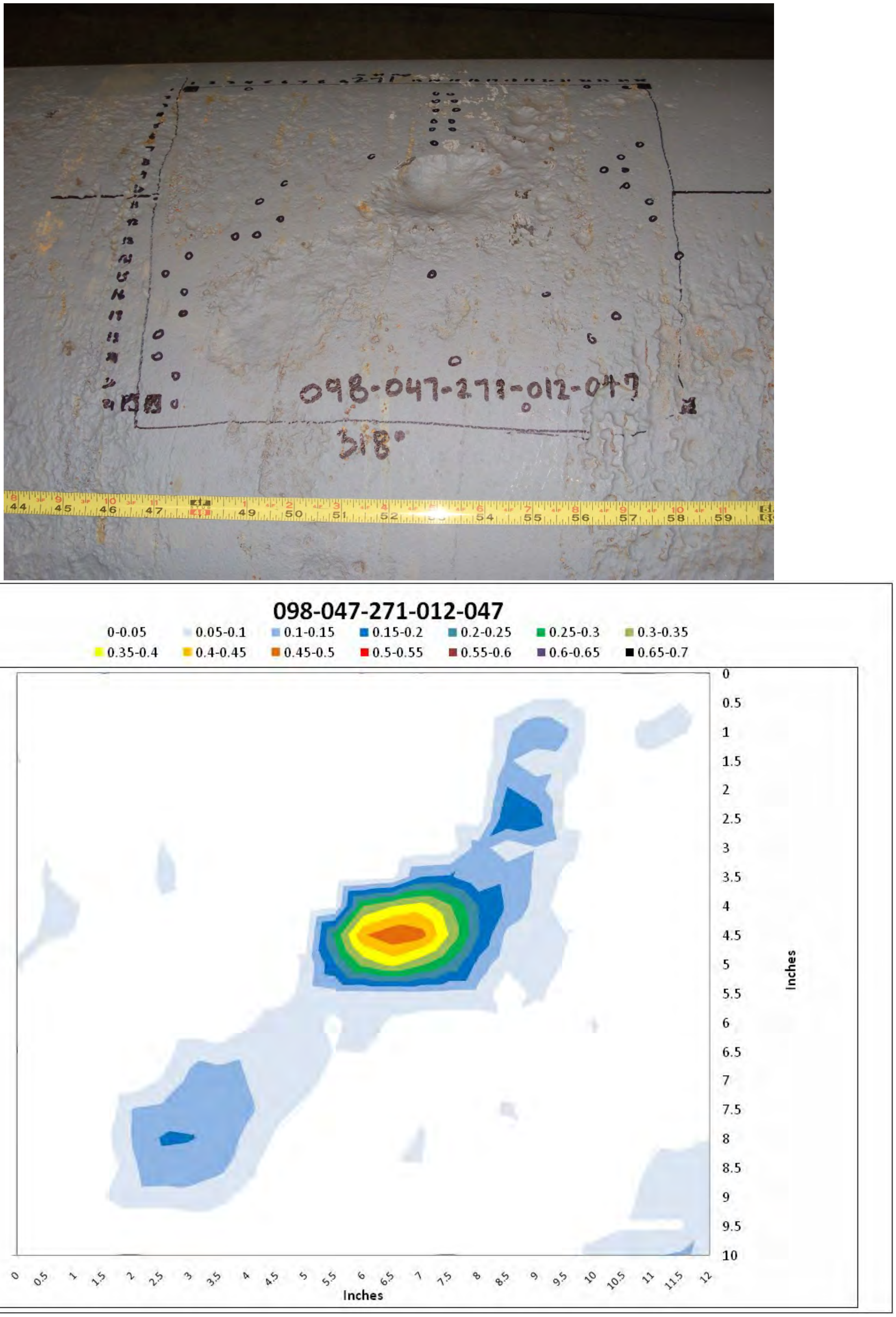


**Figure A-98(1). Pipe 98, area 098-047-271-012-047**

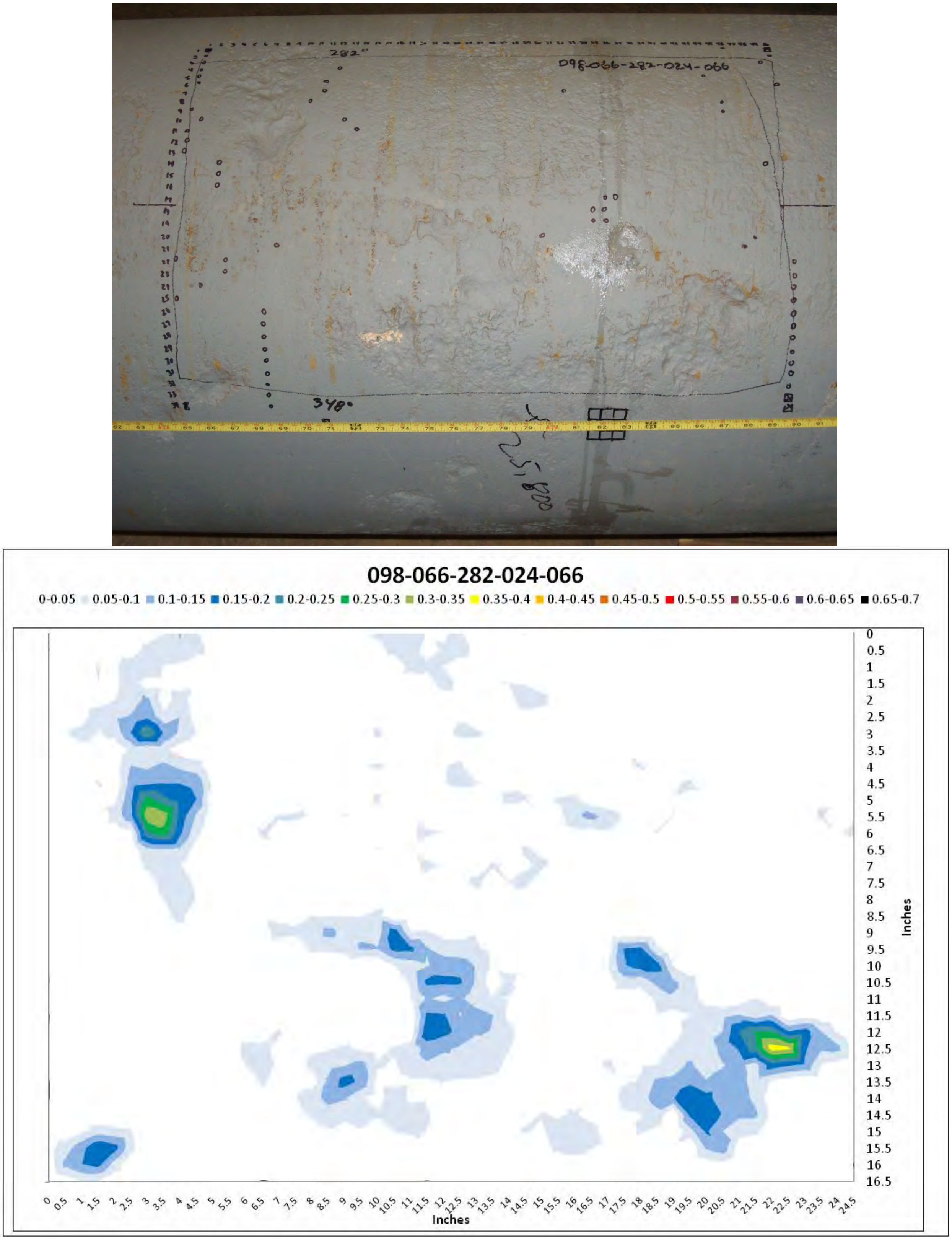


**Figure A-98(2). Pipe 98, area 098-066-282-024-066**

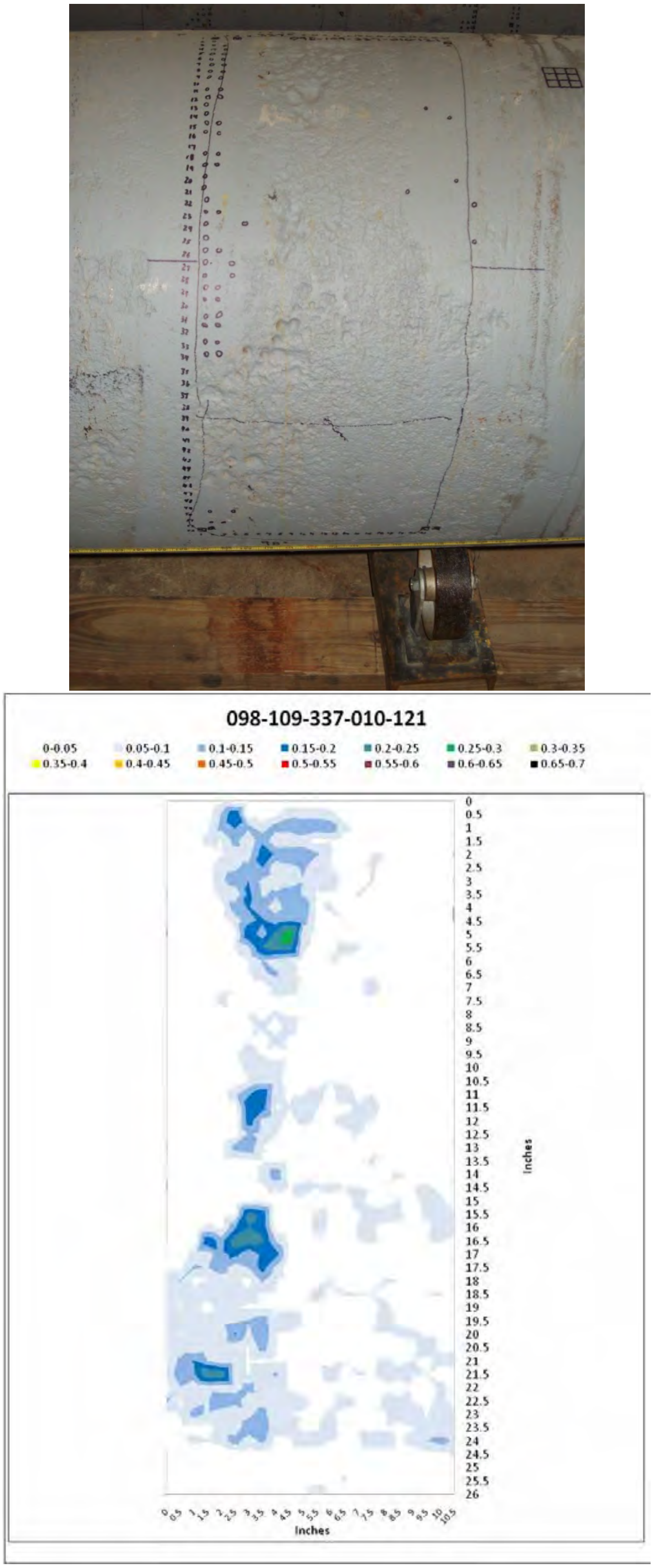


**Figure A-98(3). Pipe 98, area 098-109-337-010-121**

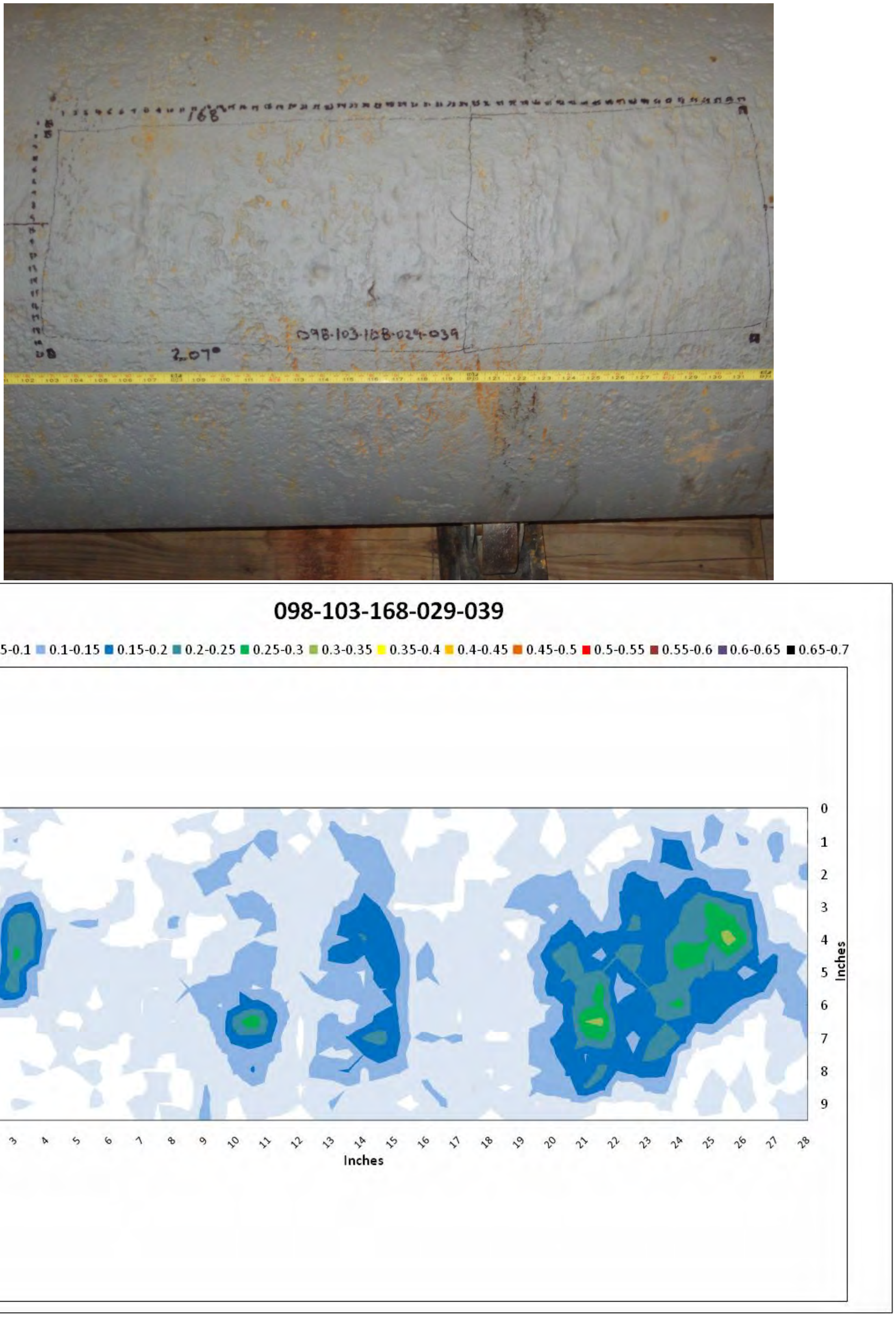


**Figure A-98(4). Pipe 98, area 098-103-168-029-039**

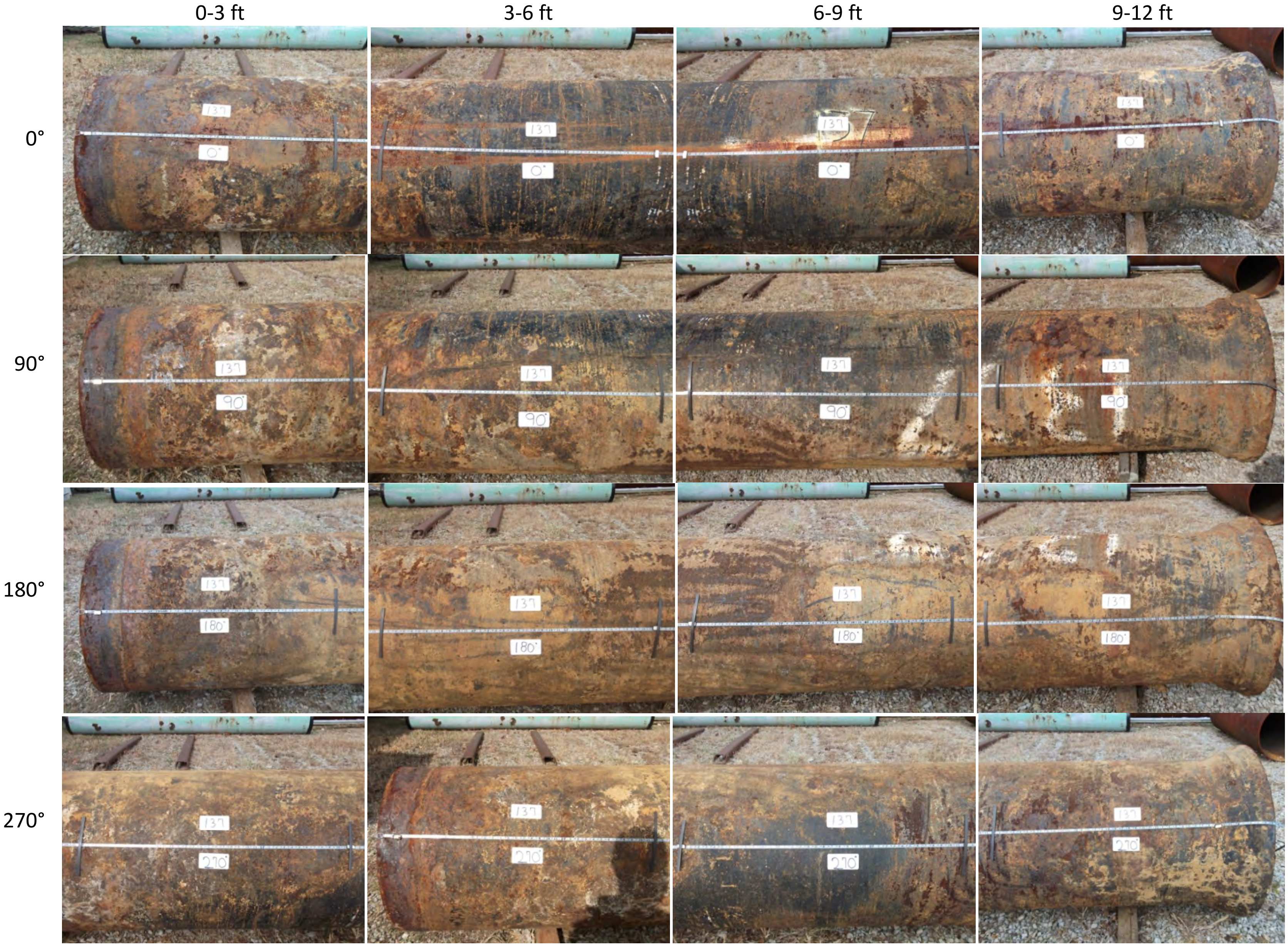


Figure A-137(1). Pipe 137 as Removed from Site

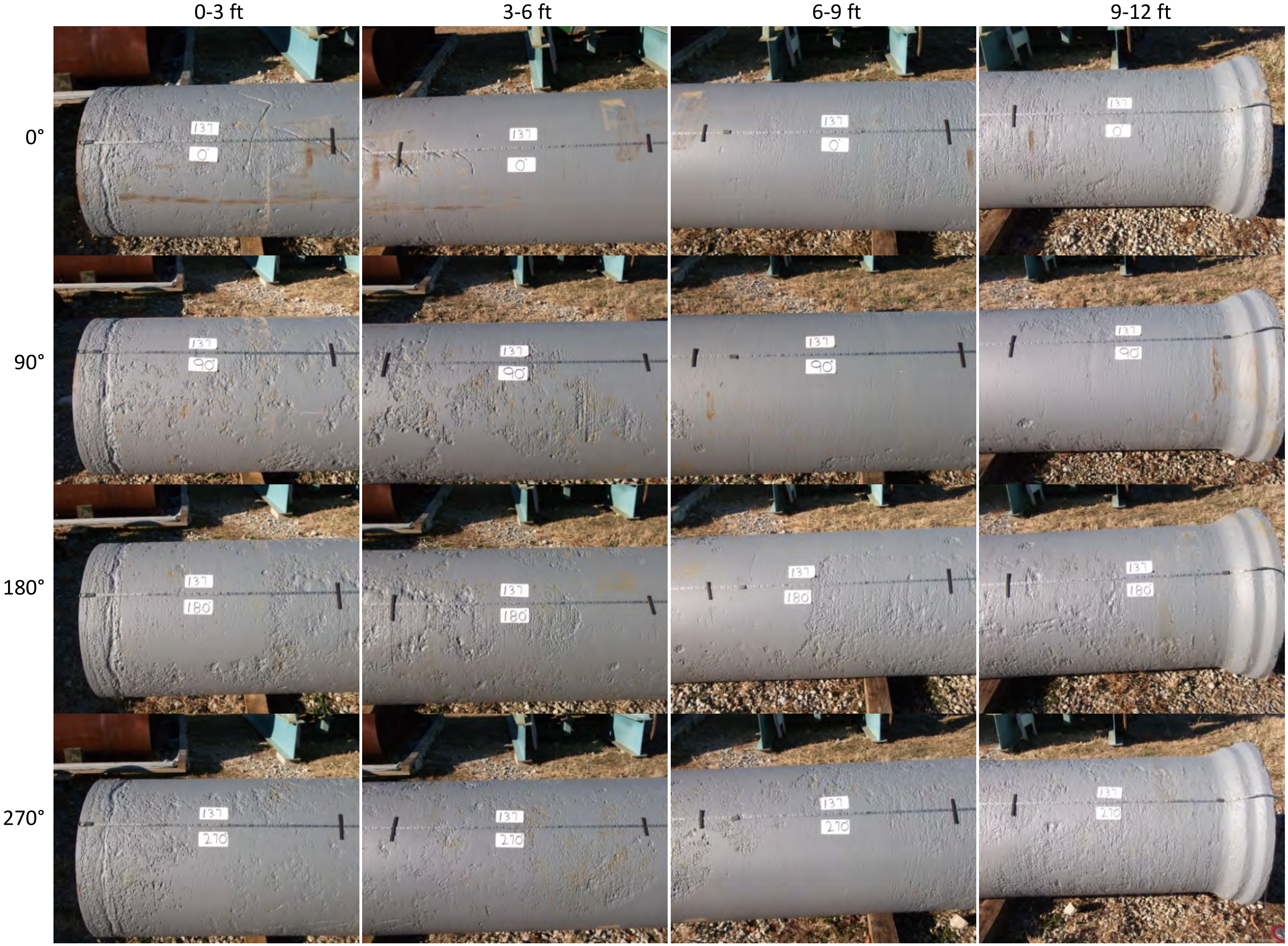


Figure A-137(2). Pipe 137 after Sandblasting

### Table A-137(1). Wall Thickness of Cast Iron at Spigot with Caliper

| Pipe Number | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| | 80˚ | x˚ | 190˚ | 290˚ |
| 137 | 0.765 | x | 0.765 | 0.773 |

### Table A-137(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)

| Pipe Number | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| | Caliper | UT | | | UT | | | UT | | |
| 137 | 0.764 | 0.749 | 0.741 | 0.730 | 0.738 | 0.736 | 0.740 | 0.766 | 0.766 | 0.757 |
| | 0.782 | 0.730 | 0.748 | 0.737 | 0.741 | 0.740 | 0.735 | x | 0.776 | 0.760 |
| | 0.764 | 0.752 | 0.731 | 0.730 | 0.741 | 0.734 | 0.742 | x | 0.785 | 0.786 |
| **Average** | 0.770 | 0.739 | | | 0.739 | | | 0.771 | | |
| **Standard Deviation** | 0.010 | 0.009 | | | 0.003 | | | 0.012 | | |
| **Minimum** | 0.764 | 0.730 | | | 0.734 | | | 0.757 | | |
| **Maximum** | 0.782 | 0.752 | | | 0.742 | | | 0.786 | | |
| **Repeat Center Cell** | - | 0.734 | | | 0.738 | | | 0.763 | | |

### Table A-137(3). Outer Diameter Measurement Using a pi Tape

| Pipe Number | Outer Diameter | | |
|---|---|---|---|
| | Spigot | Center | Bell |
| 137 | 25.800 | 25.803 | 25.810 |

### Table A- 137(4). Wall Thickness of Cement Liner at Spigot with Caliper

| Measurement (Inches) | 80˚ | x˚ | 190˚ | 290˚ |
|---|---|---|---|---|
| **Cast Iron** | 0.765 | x | 0.765 | 0.773 |
| **Cast Iron & Cement Liner** | 0.940 | x | 0.911 | 0.930 |
| **Cement Liner** | 0.175 | x | 0.146 | 0.157 |

### Table A-137(5). Pipe 137 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Bell (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| 137-025-136-025-046 | 10.7 | 111.5 | 0.243 | 31% | 0.54 | 69% | 195 | 6:30 |
| | | 109.5 | 0.239 | 31% | 0.54 | 69% | 193 | 6:26 |
| | | 120.0 | 0.231 | 30% | 0.55 | 70% | 197 | 6:34 |
| 137-017-182-033-059 | 16.9 | 103.5 | 0.238 | 31% | 0.54 | 69% | 160 | 5:20 |
| | | 122.0 | 0.206 | 26% | 0.57 | 74% | 145 | 4:50 |
| | | 113.0 | 0.202 | 26% | 0.58 | 74% | 165 | 5:30 |
| 137-010-299-040-094 | 18.8 | 113.0 | 0.207 | 27% | 0.57 | 73% | 357 | 11:54 |
| | | 109.5 | 0.189 | 24% | 0.59 | 76% | 5 | 0:10 |
| | | 124.0 | 0.181 | 23% | 0.60 | 77% | 34 | 1:08 |
| 137-000-000-010-360 | 52.7 | 146.5 | 0.361 | 46% | 0.42 | 54% | 253 | 8:26 |
| | | 146.0 | 0.328 | 42% | 0.45 | 58% | 213 | 7:06 |
| | | 146.0 | 0.324 | 42% | 0.46 | 58% | 200 | 6:40 |
| | | 146.5 | 0.321 | 41% | 0.46 | 59% | 160 | 5:20 |
| | | 146.5 | 0.320 | 41% | 0.46 | 59% | 260 | 8:40 |

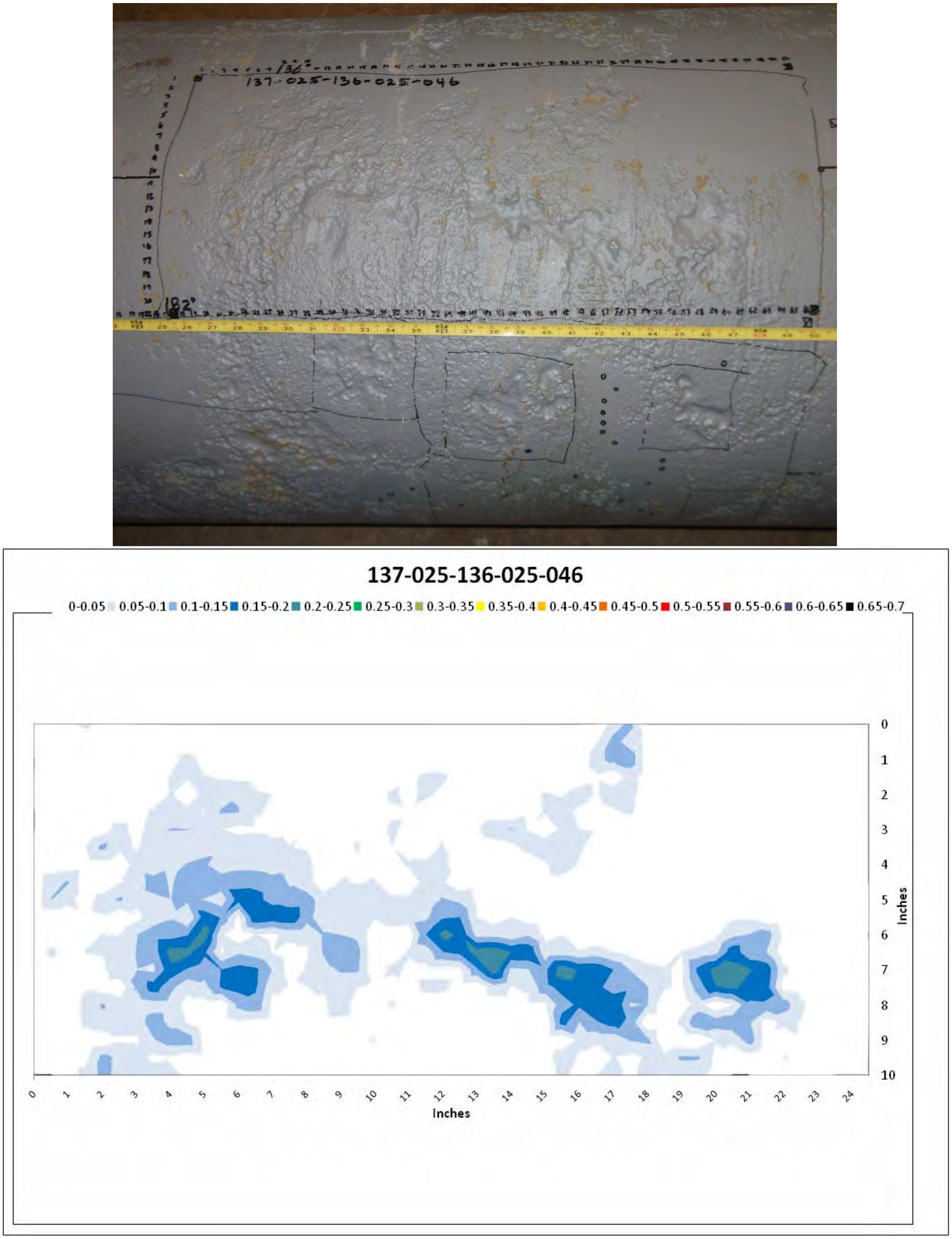


**Figure A-137(1). Pipe 137, area 137-025-136-025-046**

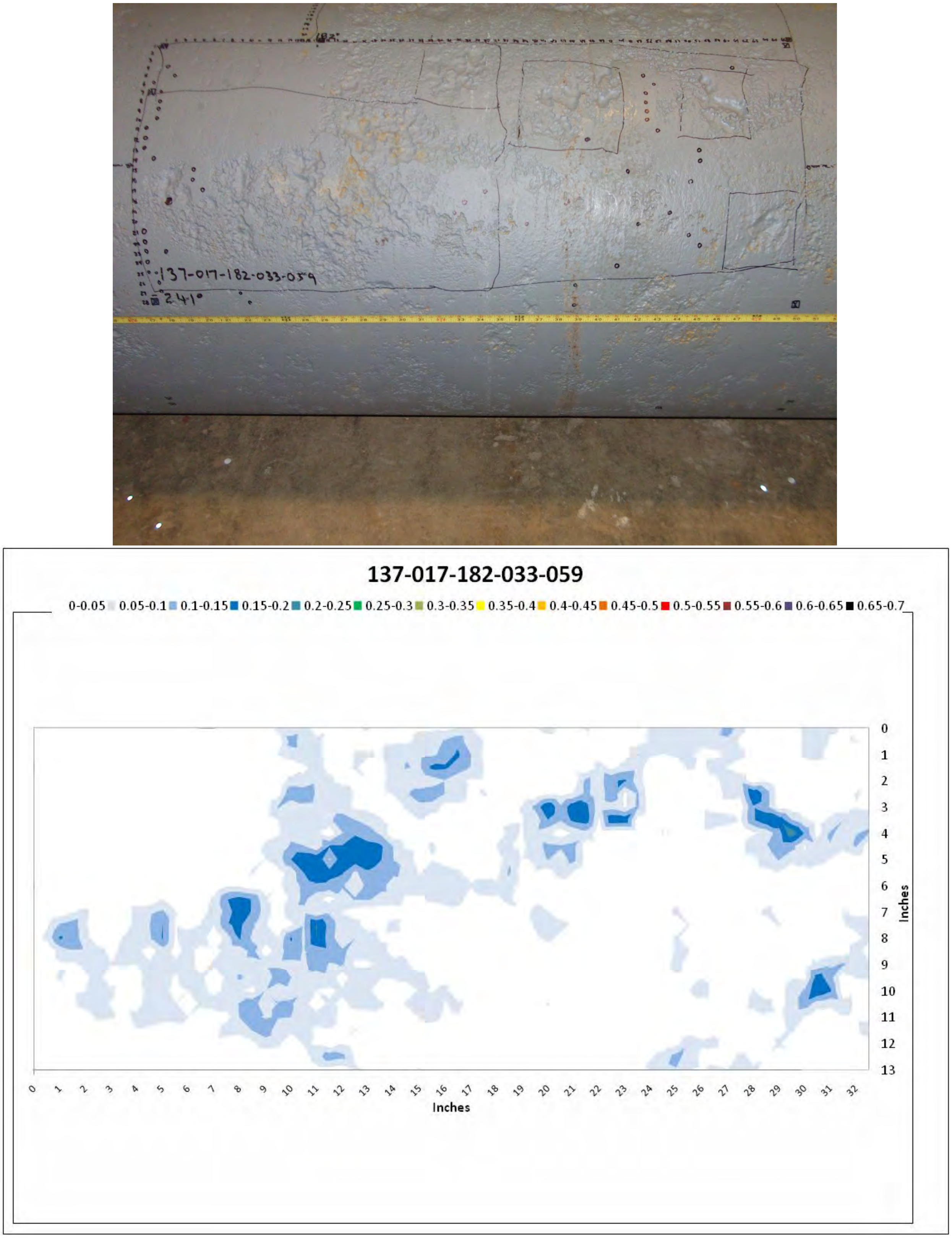


**Figure A-137(2). Pipe 137, area 137-017-182-033-059**

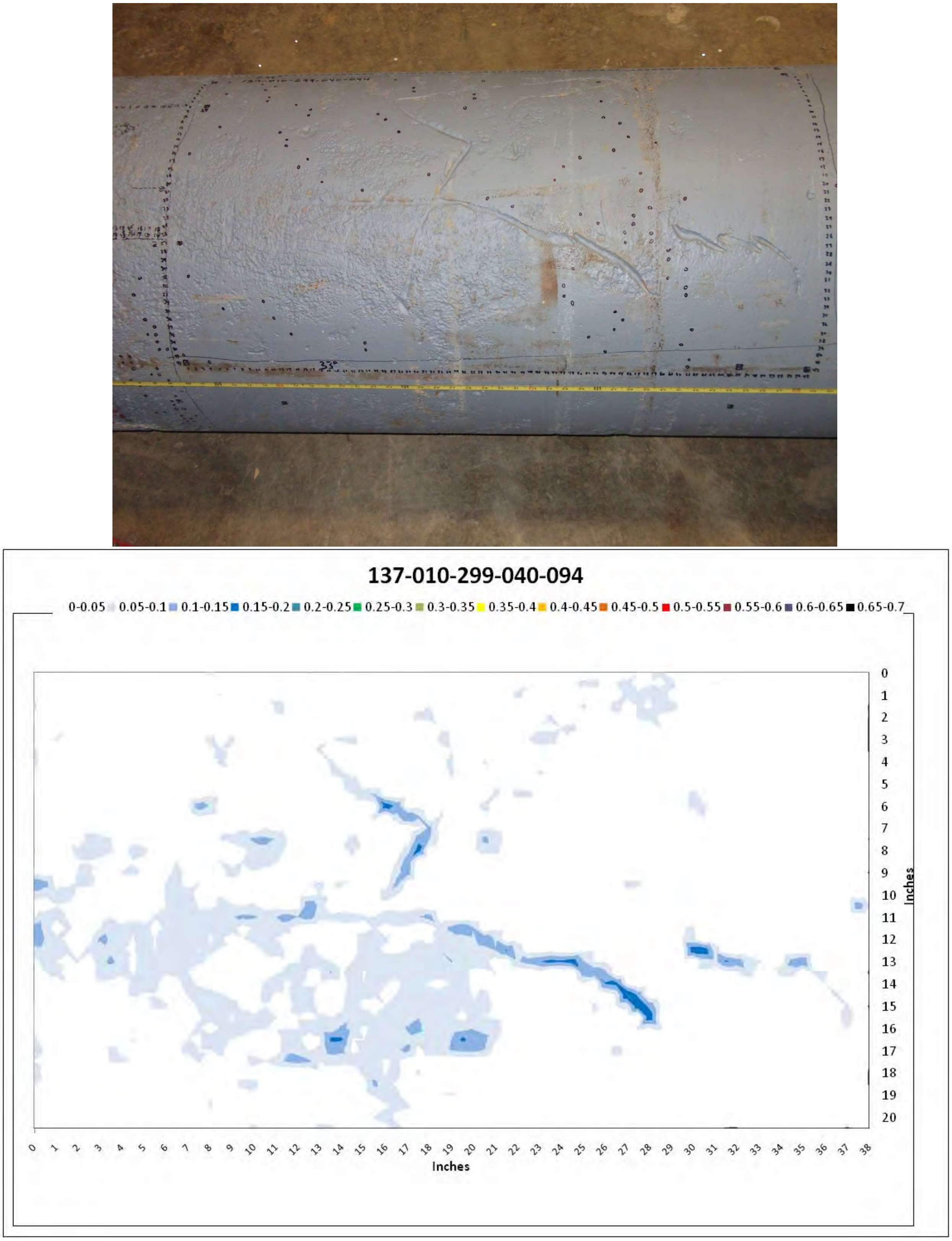


**Figure A-137(3). Pipe 137, area 137-010-299-040-094**

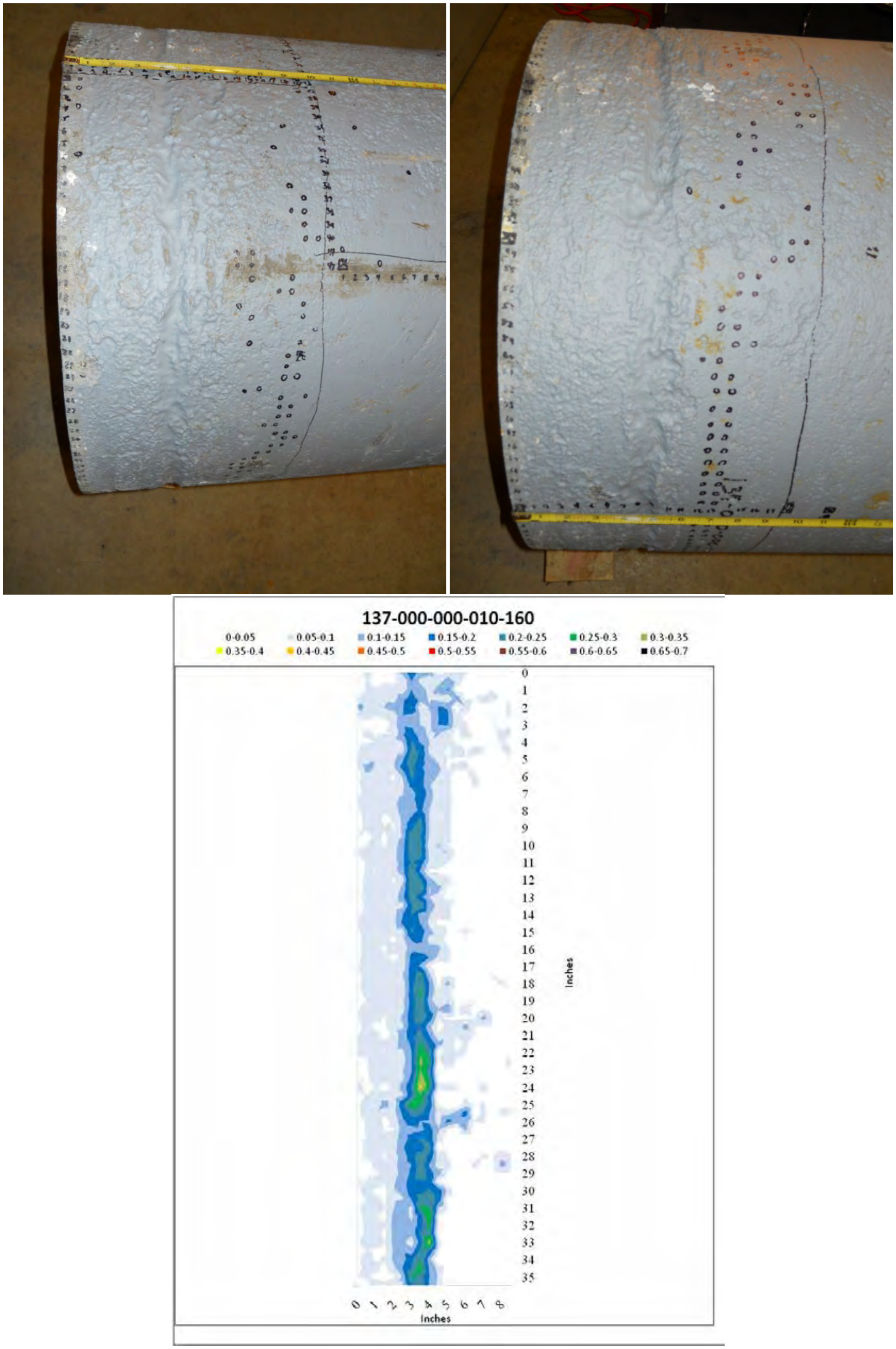


**Figure A-137(4). Pipe 137, area 137-000-000-010-160**

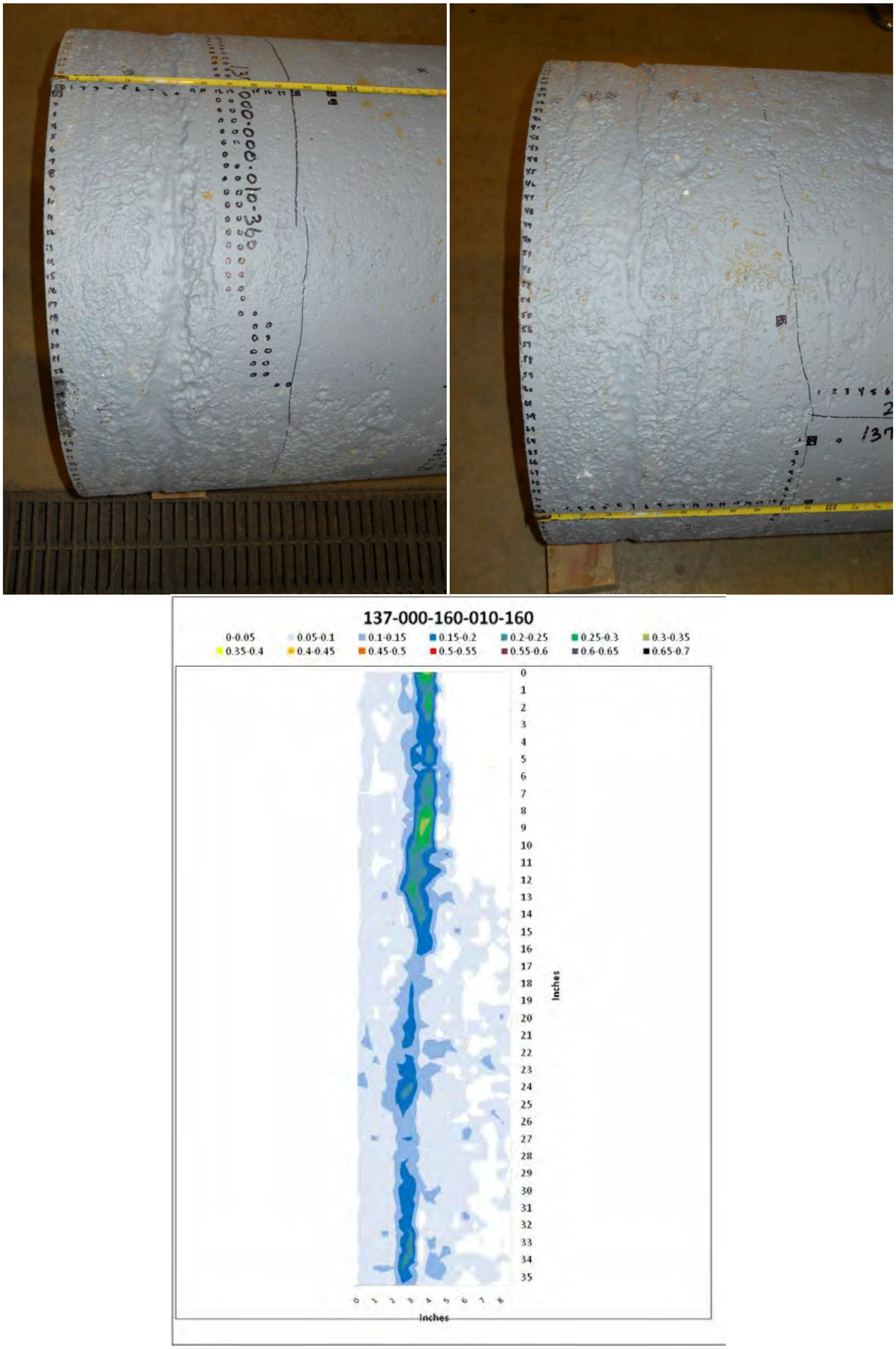


Figure A-137(5). Pipe 137, area 137-000-160-010-160

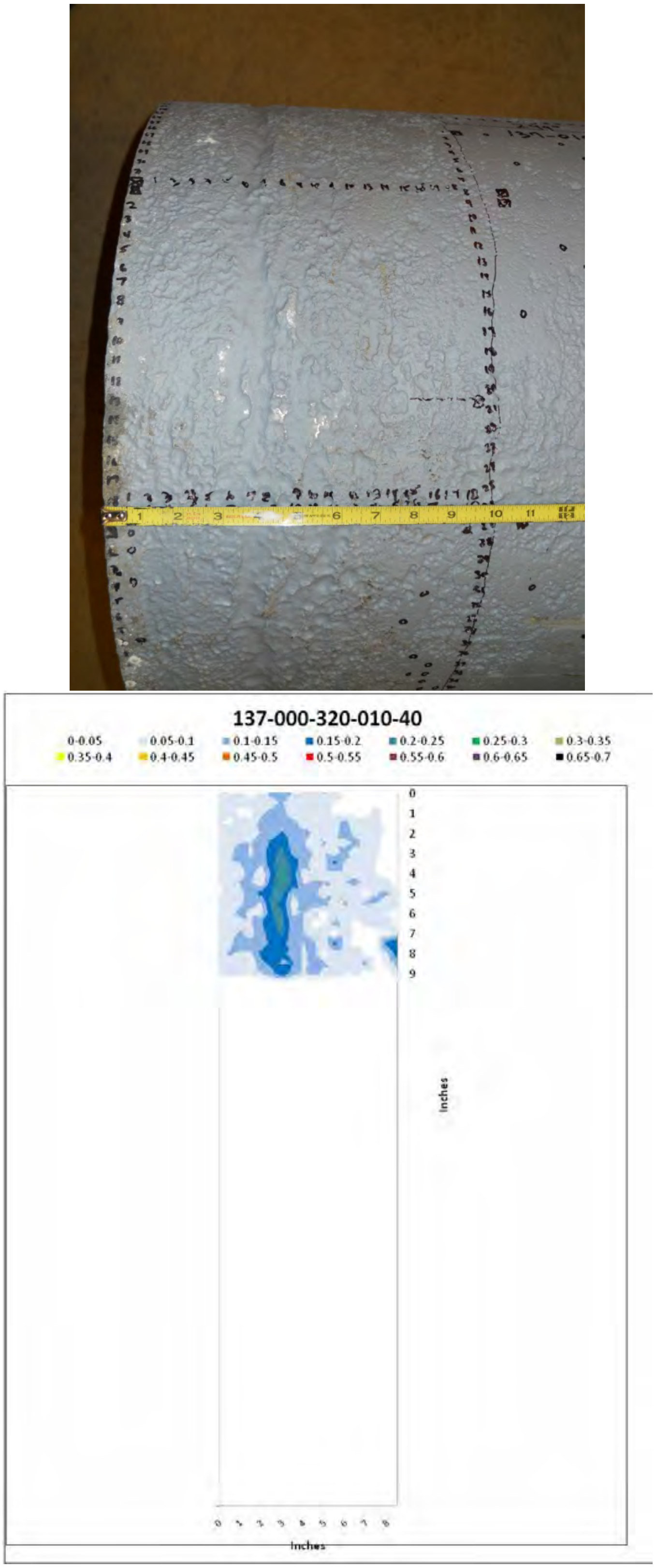


Figure A-137(6). Pipe 137, area 137-000-320-010-40

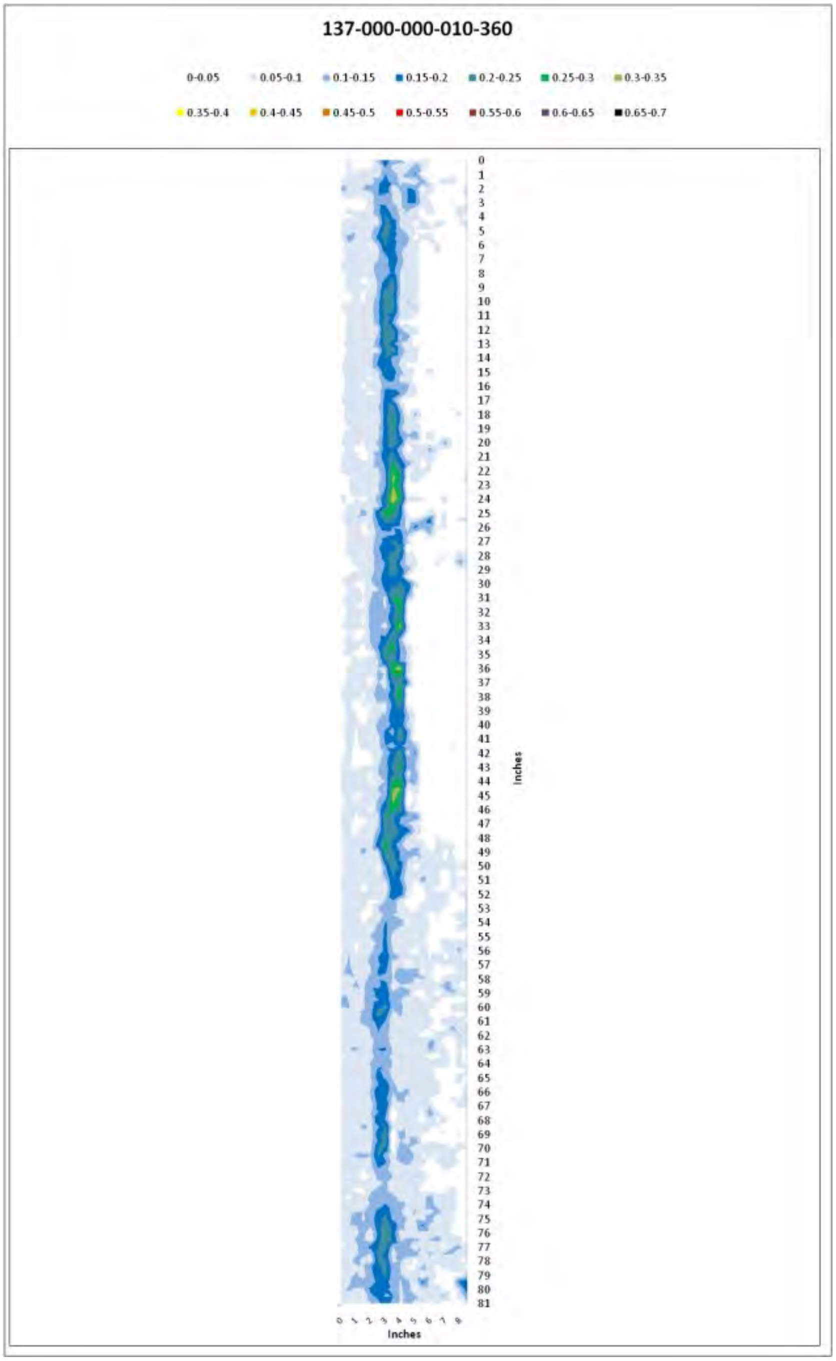


Figure A-137(7). All depths at the spigot for Pipe 137 from 0° to 360º combined into one image, area 137-000-000-010-360

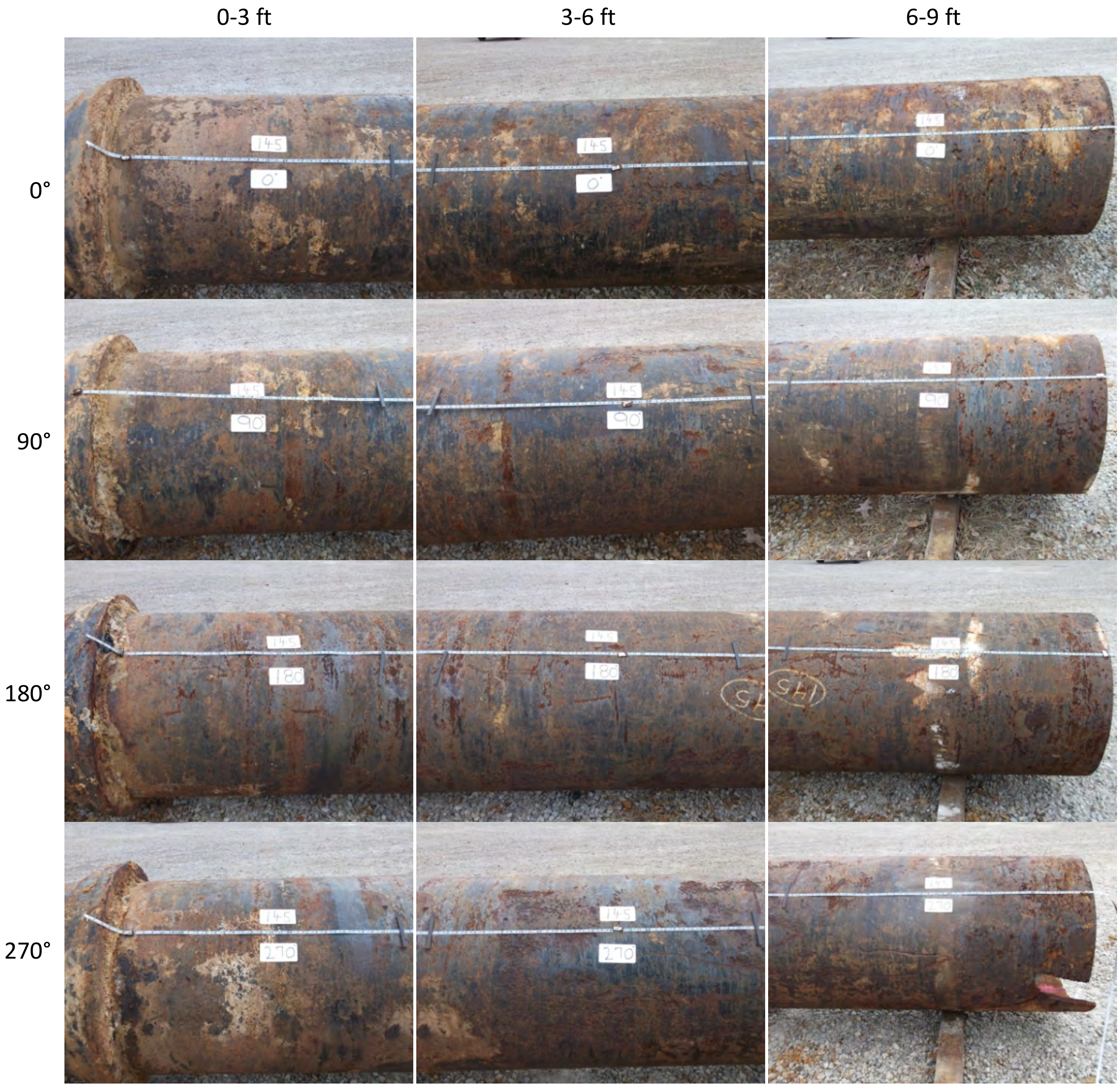


**Figure A-145(1). Pipe 145 as Removed from Site**

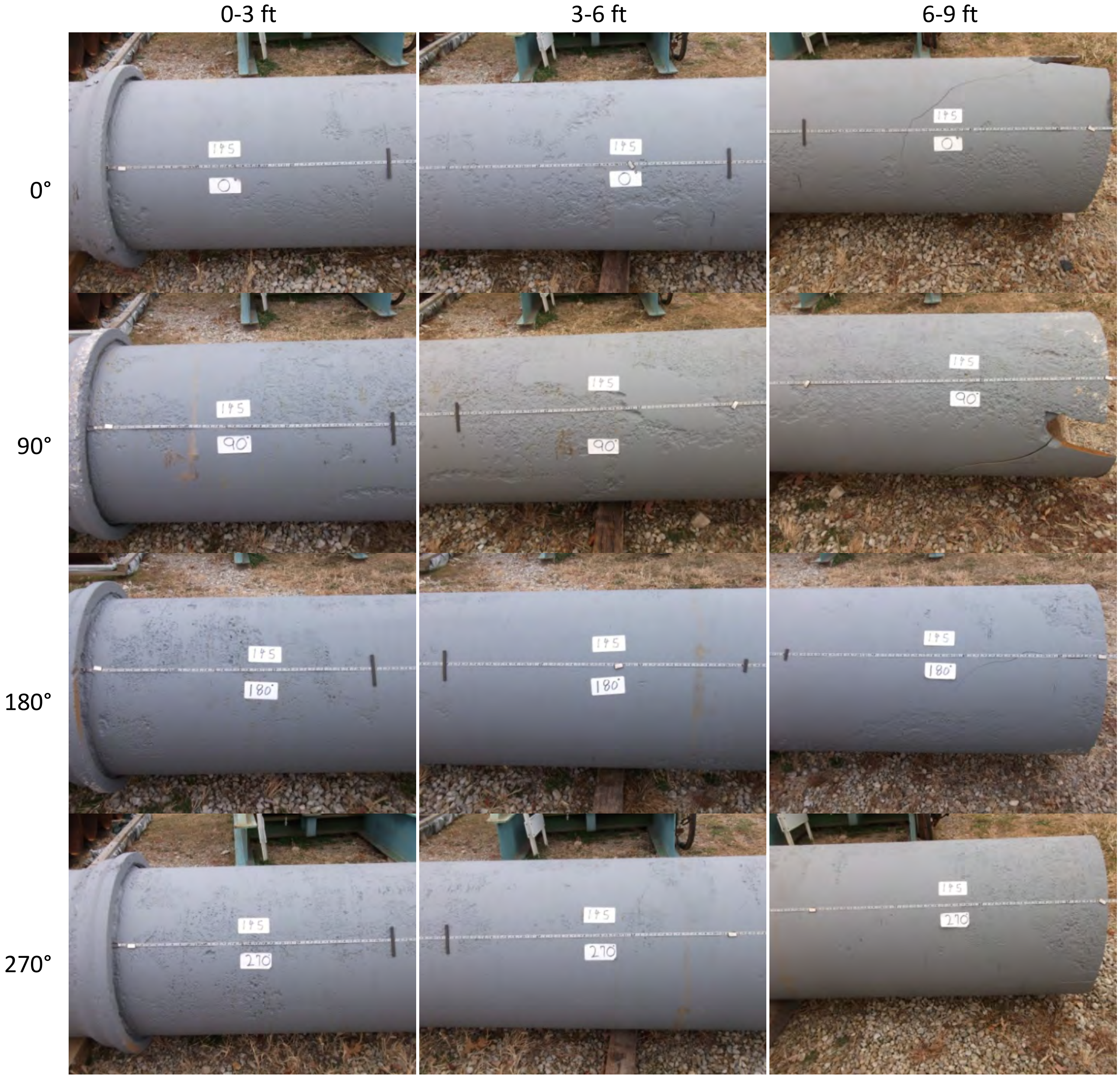


**Figure A-145(2). Pipe 145 after Sandblasting**

### Table A-145(1). Wall Thickness of Cast Iron at Spigot with Caliper

| Pipe Number | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| | 5˚ | 335˚ | 345˚ | 355˚ |
| 145 | 0.789 | 0.782 | 0.784 | 0.787 |

### Table A-145(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)

| Pipe Number | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| | Caliper | UT | | | UT | | | UT | | |
| 145 | 0.791 | 0.765 | 0.766 | 0.761 | 0.808 | 0.814 | 0.790 | 0.764 | 0.767 | 0.759 |
| | 0.794 | 0.771 | 0.770 | 0.763 | 0.815 | 0.782 | 0.807 | 0.757 | 0.783 | 0.768 |
| | 0.785 | 0.765 | 0.759 | 0.749 | 0.817 | 0.788 | 0.811 | 0.760 | 0.747 | 0.762 |
| **Average** | 0.790 | 0.763 | | | 0.804 | | | 0.763 | | |
| **Standard Deviation** | 0.005 | 0.007 | | | 0.013 | | | 0.010 | | |
| **Minimum** | 0.785 | 0.749 | | | 0.782 | | | 0.747 | | |
| **Maximum** | 0.794 | 0.771 | | | 0.817 | | | 0.783 | | |
| **Repeat Center Cell** | - | 0.751 | | | 0.780 | | | 0.765 | | |

### Table A-145(3). Outer Diameter Measurement Using a pi Tape

| Pipe Number | Outer Diameter | | |
|---|---|---|---|
| | Spigot | Center | Bell |
| 145 | 25.825 | 25.803 | 25.803 |

### Table A-145(4). Wall Thickness of Cement Liner at Spigot with Caliper

| Measurement (Inches) | 5˚ | 335˚ | 345˚ | 355˚ |
|---|---|---|---|---|
| **Cast Iron** | 0.789 | 0.782 | 0.784 | 0.787 |
| **Cast Iron & Cement Liner** | 1.106 | 1.105 | 1.091 | 1.098 |
| **Cement Liner** | 0.317 | 0.323 | 0.307 | 0.311 |

Table A-145(5).  Scanned Pipe 145 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Spigot (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| H11 | 29.7 | 12.9 | 0.3343 | 44% | 0.4287 | 56% | 80 | 2:39 |
| | | 4.8 | 0.2216 | 29% | 0.5414 | 71% | 13 | 0:26 |
| | | 4.4 | 0.2441 | 32% | 0.5189 | 68% | 38 | 1:15 |
| | | 4.8 | 0.2118 | 28% | 0.5512 | 72% | 71 | 2:22 |
| H12 | 33.9 | 2.0 | 0.2677 | 35% | 0.4953 | 65% | 151 | 5:02 |
| | | 6.3 | 0.2142 | 28% | 0.5488 | 72% | 122 | 4:03 |
| | | 10.4 | 0.2535 | 33% | 0.5095 | 67% | 113 | 3:46 |
| | | 8.9 | 0.2370 | 31% | 0.5260 | 69% | 106 | 3:32 |
| | | 7.8 | 0.2528 | 33% | 0.5102 | 67% | 100 | 3:19 |
| | | 13.3 | 0.2272 | 30% | 0.5358 | 70% | 97 | 3:14 |
| | | 15.3 | 0.2673 | 35% | 0.4957 | 65% | 100 | 3:19 |
| | | 18.9 | 0.3740 | 49% | 0.3890 | 51% | 100 | 3:19 |
| | | 18.3 | 0.3173 | 42% | 0.4457 | 58% | 122 | 4:03 |
| | | 17.8 | 0.2559 | 34% | 0.5071 | 66% | 113 | 3:46 |
| | | 19.8 | 0.2760 | 36% | 0.4870 | 64% | 111 | 3:41 |
| | | 19.8 | 0.3083 | 40% | 0.4547 | 60% | 64 | 2:08 |
| H13 | 20.4 | 27.8 | 0.2449 | 32% | 0.5181 | 68% | 193 | 6:25 |
| | | 28.9 | 0.2362 | 31% | 0.5268 | 69% | 198 | 6:35 |
| | | 24.4 | 0.1898 | 25% | 0.5732 | 75% | 202 | 6:43 |
| | | 26.3 | 0.1850 | 24% | 0.5780 | 76% | 217 | 7:14 |
| | | 28.9 | 0.1898 | 25% | 0.5732 | 75% | 213 | 7:05 |
| H14 | -3.6 | 37.4 | 0.1906 | 25% | 0.5724 | 75% | 286 | 9:32 |
| | | 35.3 | 0.1835 | 24% | 0.5795 | 76% | 288 | 9:36 |
| H21 | 12.9 | 64.9 | 0.2102 | 26% | 0.5938 | 74% | 7 | 0:13 |
| | | 63.4 | 0.1890 | 24% | 0.6150 | 76% | 20 | 0:40 |
| | | 60.4 | 0.1858 | 23% | 0.6182 | 77% | 9 | 0:17 |
| | | 55.9 | 0.1890 | 24% | 0.6150 | 76% | 7 | 0:13 |
| | | 54.0 | 0.1902 | 24% | 0.6138 | 76% | 9 | 0:17 |
| H22 | -1.1 | - | - | - | - | - | - | - |
| H23 | 35.4 | 60.4 | 0.3319 | 41% | 0.4721 | 59% | 255 | 8:30 |

| **Defect Area** | **Total Volume Loss (in.$^3$)** | **Dist From Spigot (in.)** | **Maximum Depths In Defect Area (in.)** | **% Loss** | **Remaining (in.)** | **% Remaining** | **Clock (Degrees)** | **Clock (12hr)** |
|---|---|---|---|---|---|---|---|---|
| | | 50.4 | 0.2236 | 28% | 0.5804 | 72% | 242 | 8:04 |
| | | 55.9 | 0.2157 | 27% | 0.5883 | 73% | 251 | 8:21 |
| | | 58.5 | 0.2535 | 32% | 0.5505 | 68% | 244 | 8:08 |
| | | 48.9 | 0.2154 | 27% | 0.5886 | 73% | 242 | 8:03 |
| H24 | 21.7 | 42.5 | 0.2465 | 31% | 0.5575 | 69% | 293 | 9:46 |
| | | 54.0 | 0.3272 | 41% | 0.4768 | 59% | 311 | 10:21 |
| | | 57.0 | 0.2578 | 32% | 0.5462 | 68% | 297 | 9:54 |
| H31 | 1.8 | 75.0 | 0.1433 | 19% | 0.6197 | 81% | 27 | 0:53 |
| H32 | 4.5 | 88.9 | 0.2000 | 26% | 0.5630 | 74% | 171 | 5:41 |
| H33 | 23 | 74.4 | 0.2106 | 28% | 0.5524 | 72% | 195 | 6:30 |
| | | 75.9 | 0.2012 | 26% | 0.5618 | 74% | 206 | 6:52 |
| H34 | 1.6 | 98.0 | 0.3161 | 41% | 0.4469 | 59% | 304 | 10:08 |
| | | 100.0 | 0.2012 | 26% | 0.5618 | 74% | 304 | 10:08 |

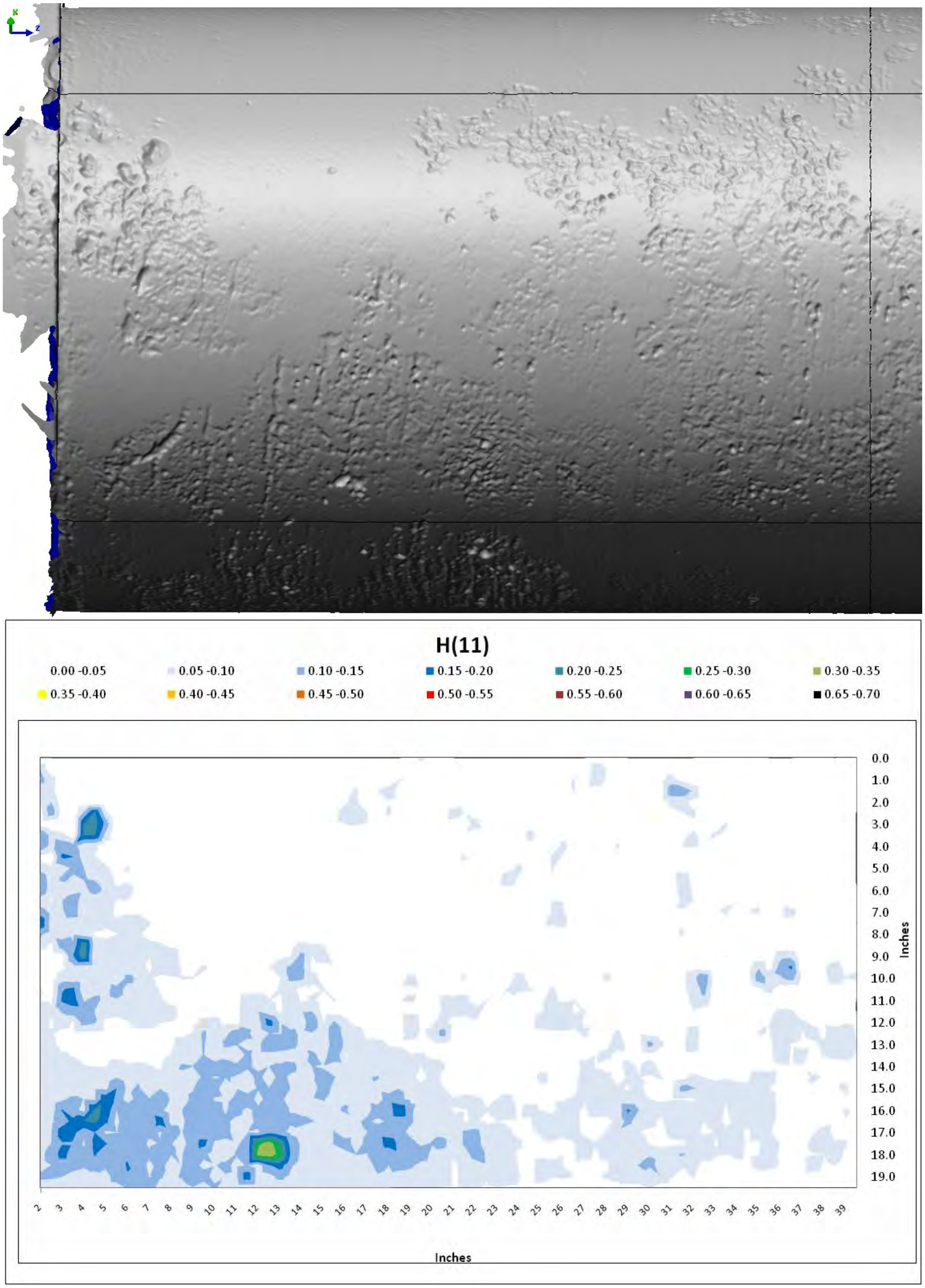


Figure A-145(1). Pipe 145, 0-3 feet and 0-90 degrees

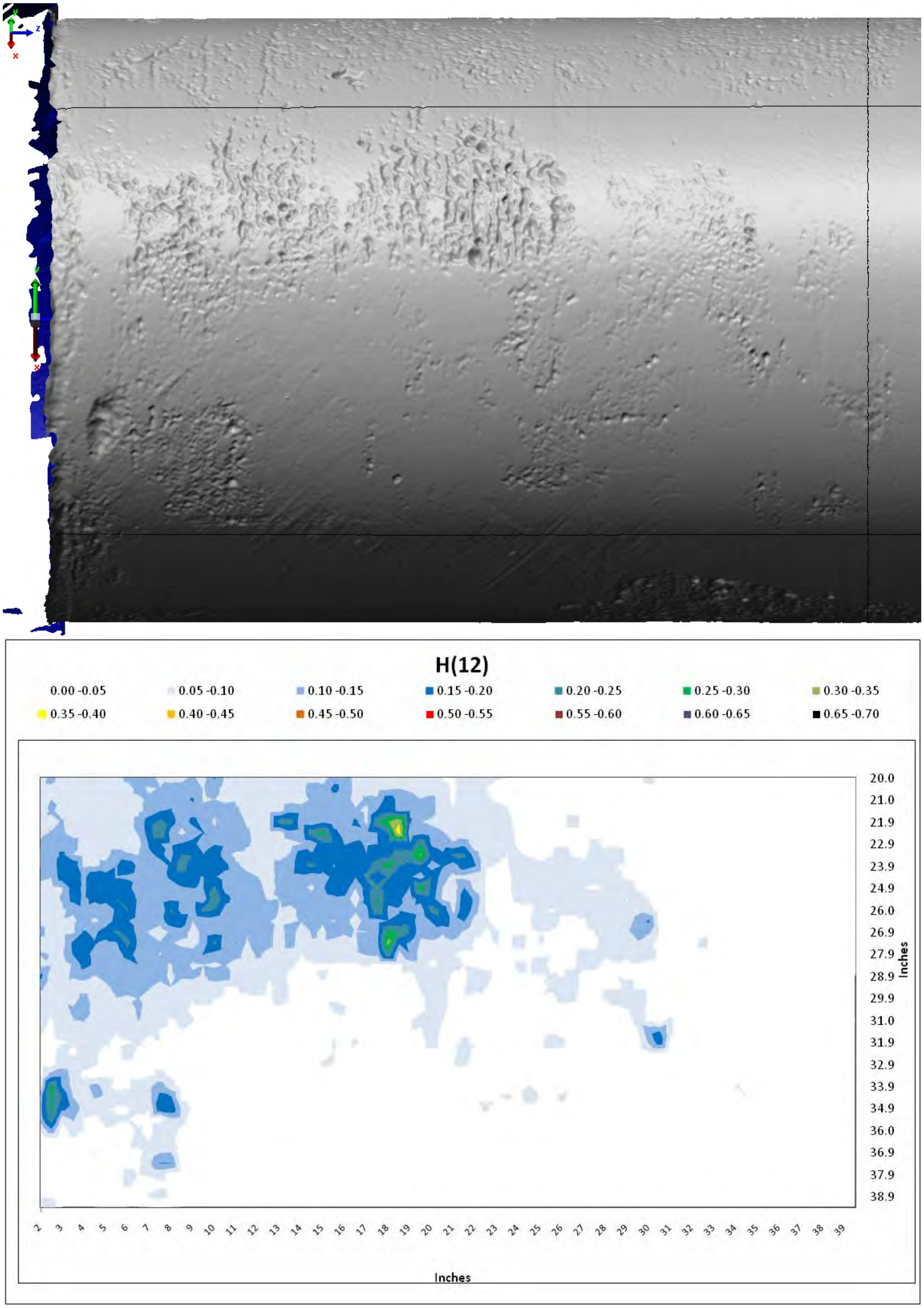


**Figure A-145(2). 0-3 feet and 90-180 degrees**

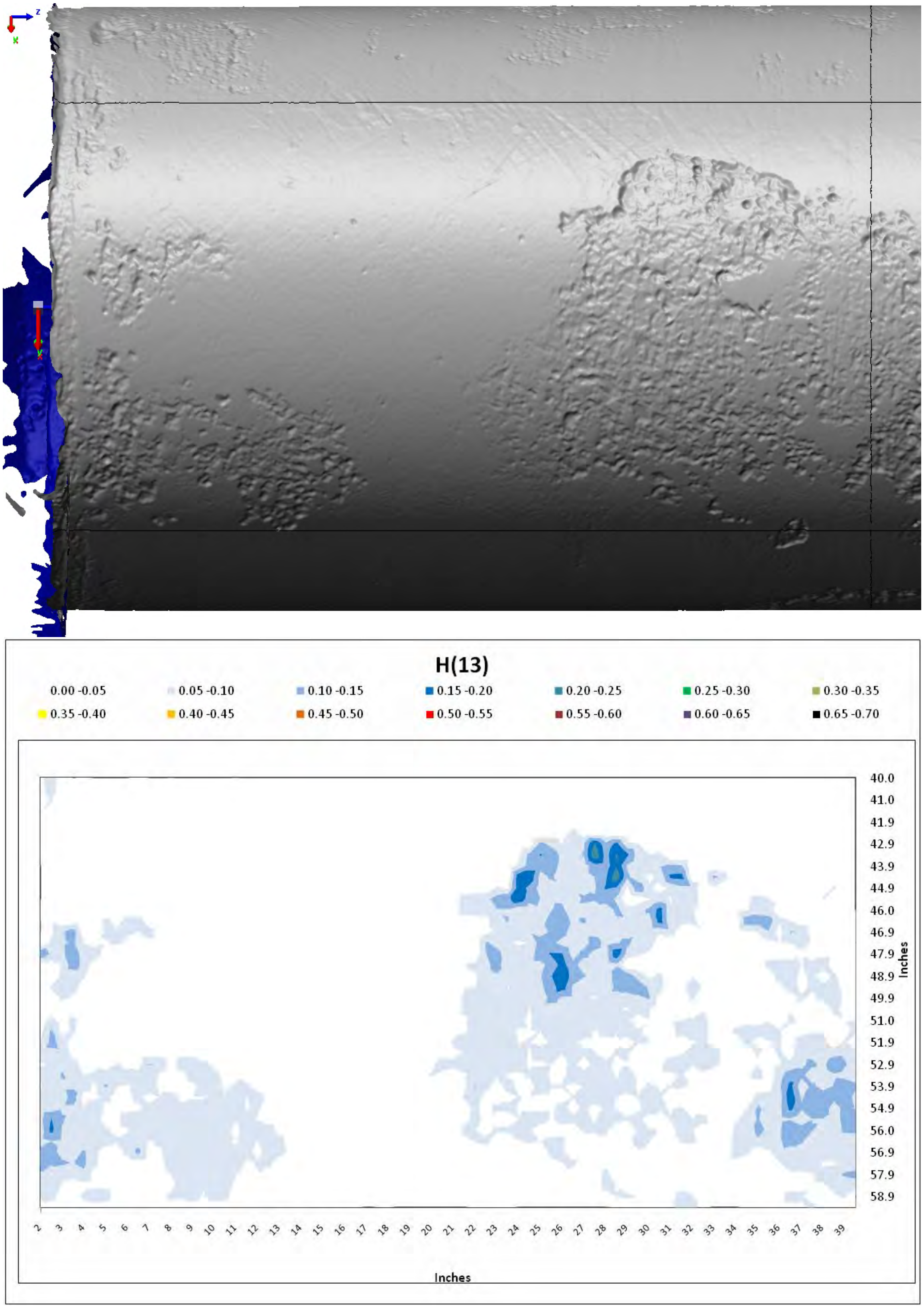


Figure A-145(3). 0-3 feet and 180-270 degrees

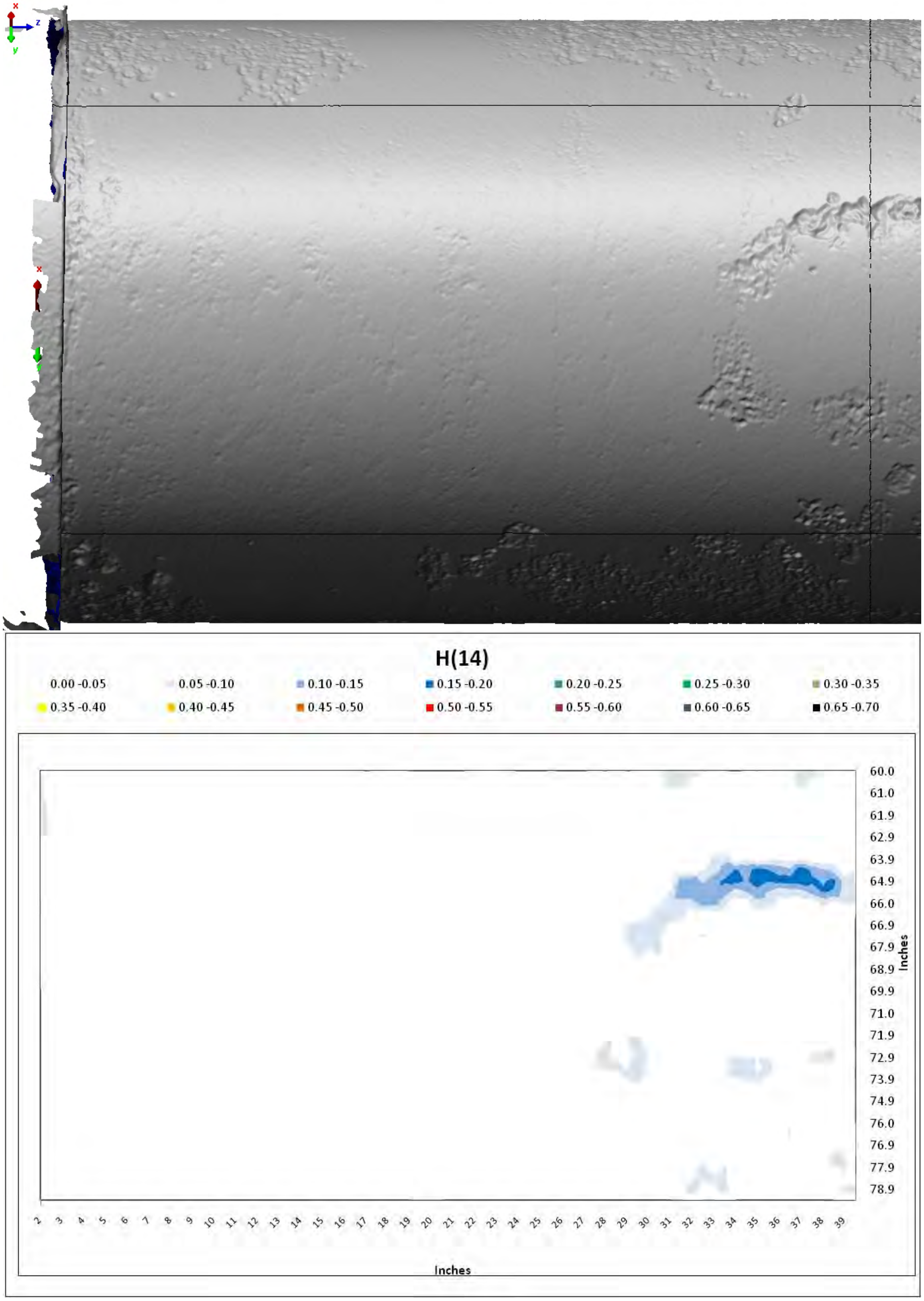


Figure A-145(4). 0-3 feet and 270-300 degrees

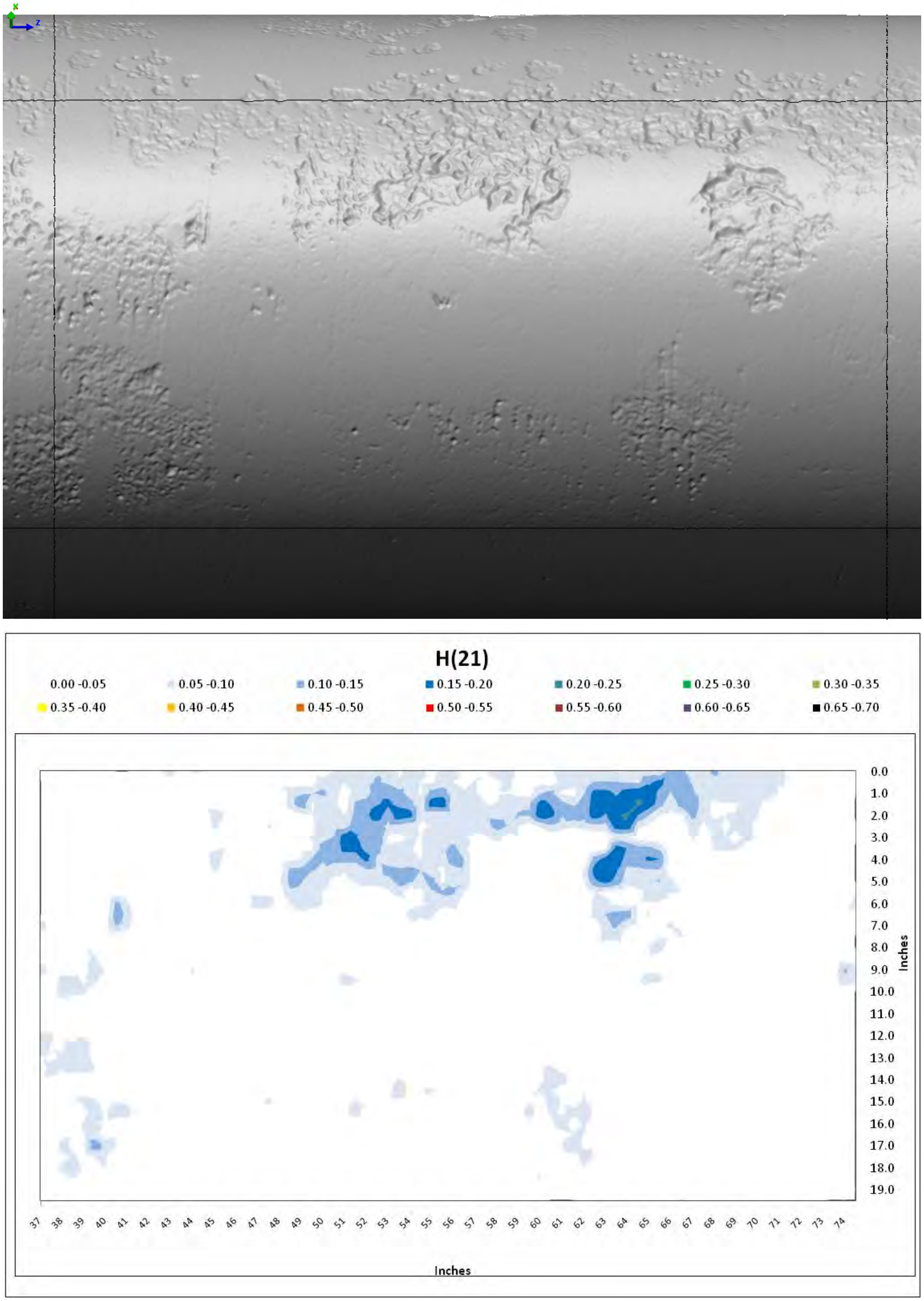


Figure A-145(5). 3-6 feet and 0-90 degrees

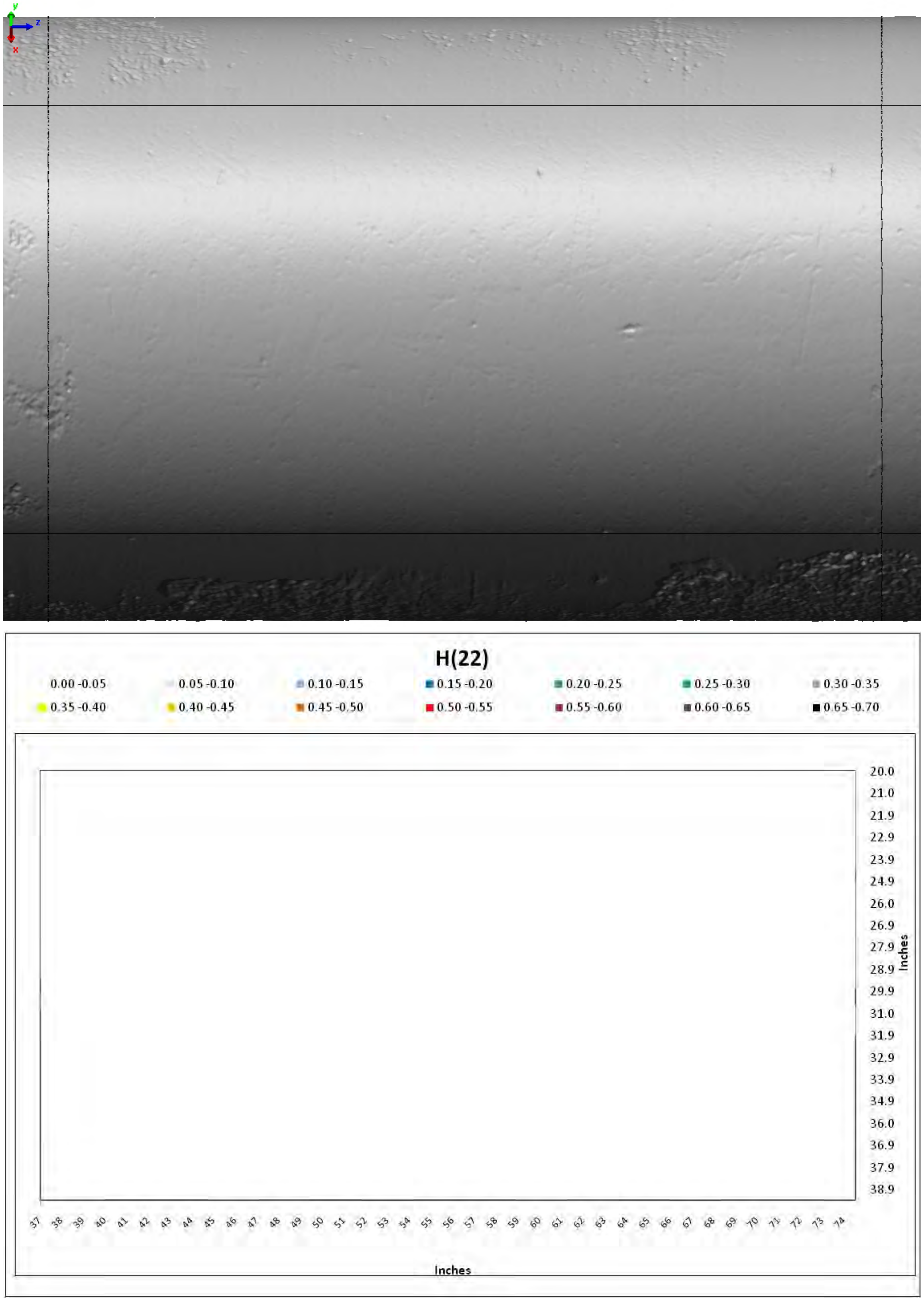


**Figure A-145(6). 3-6 feet and 90-180 degrees**

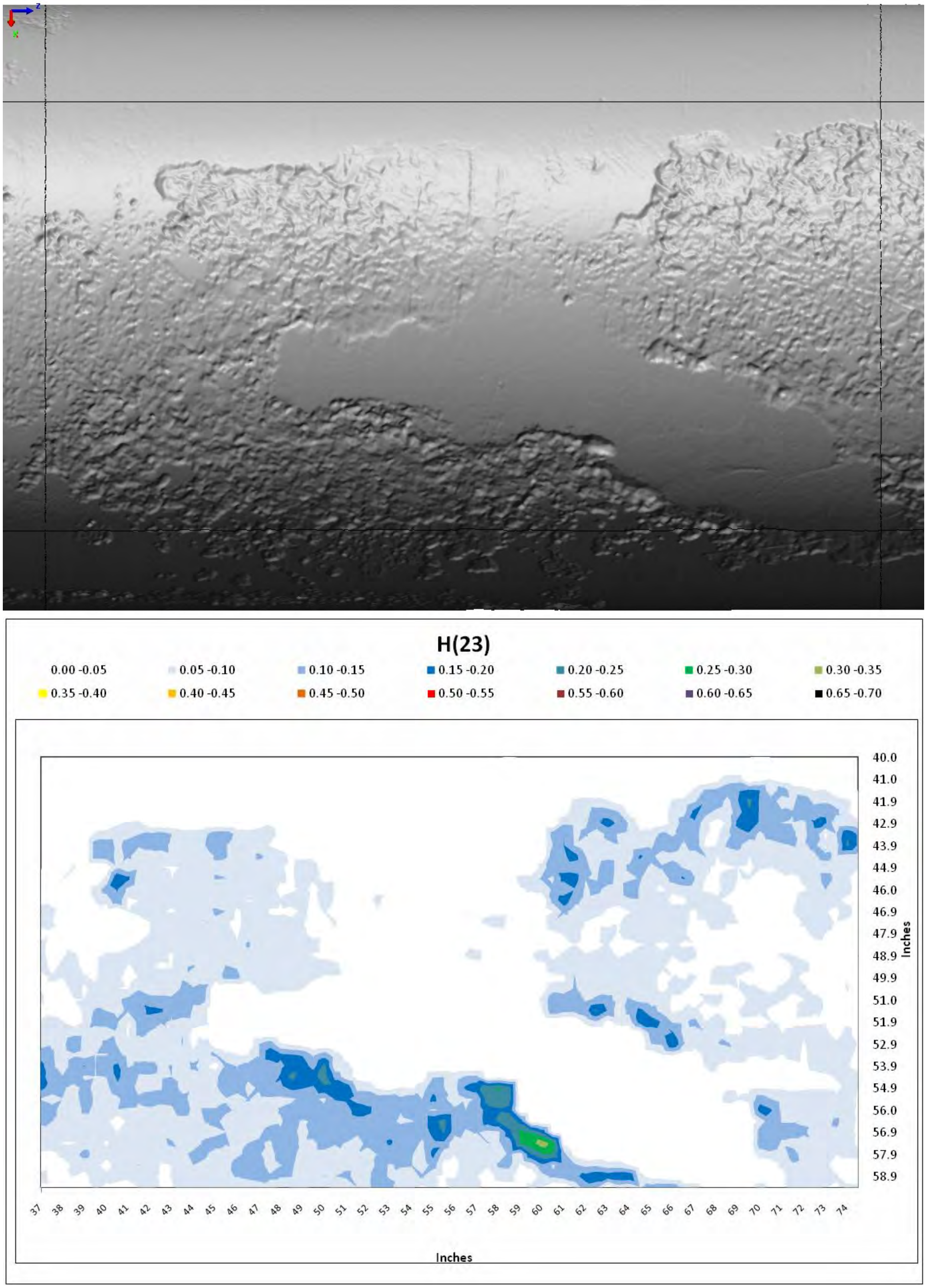


Figure A-145(7). 3-6 feet and 180-270 degrees

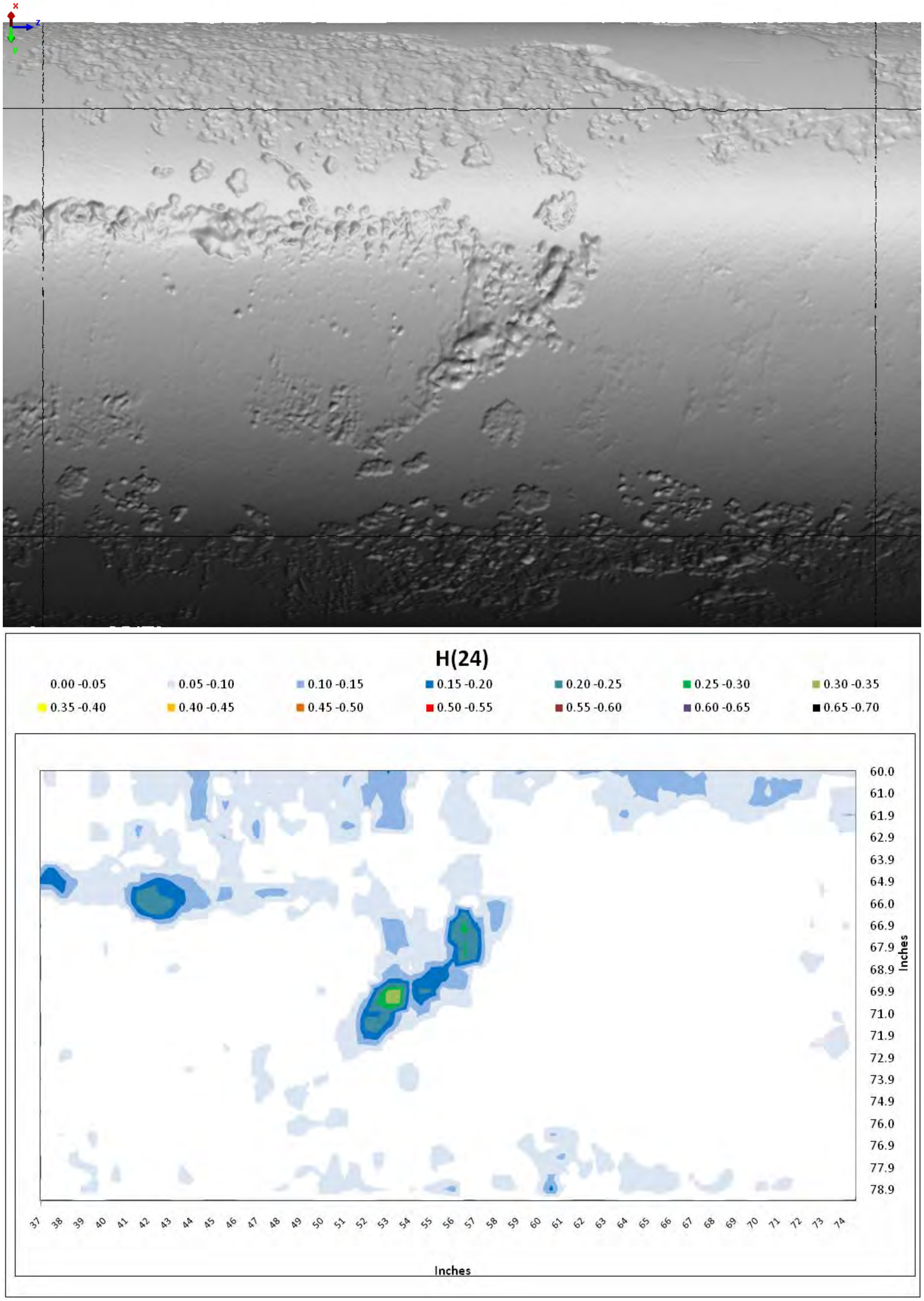


**Figure A-145(8). 3-6 feet and 270-300 degrees**

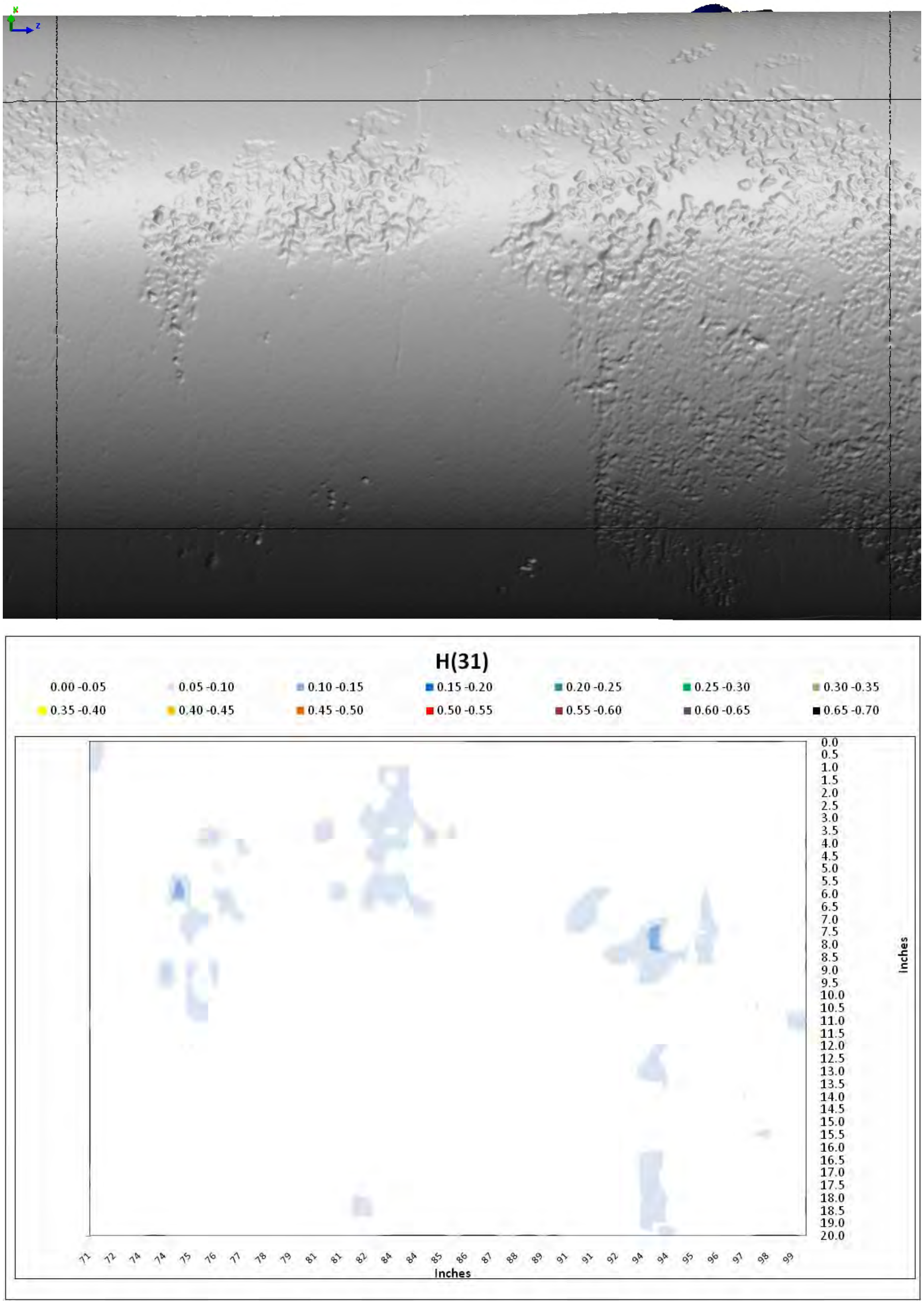
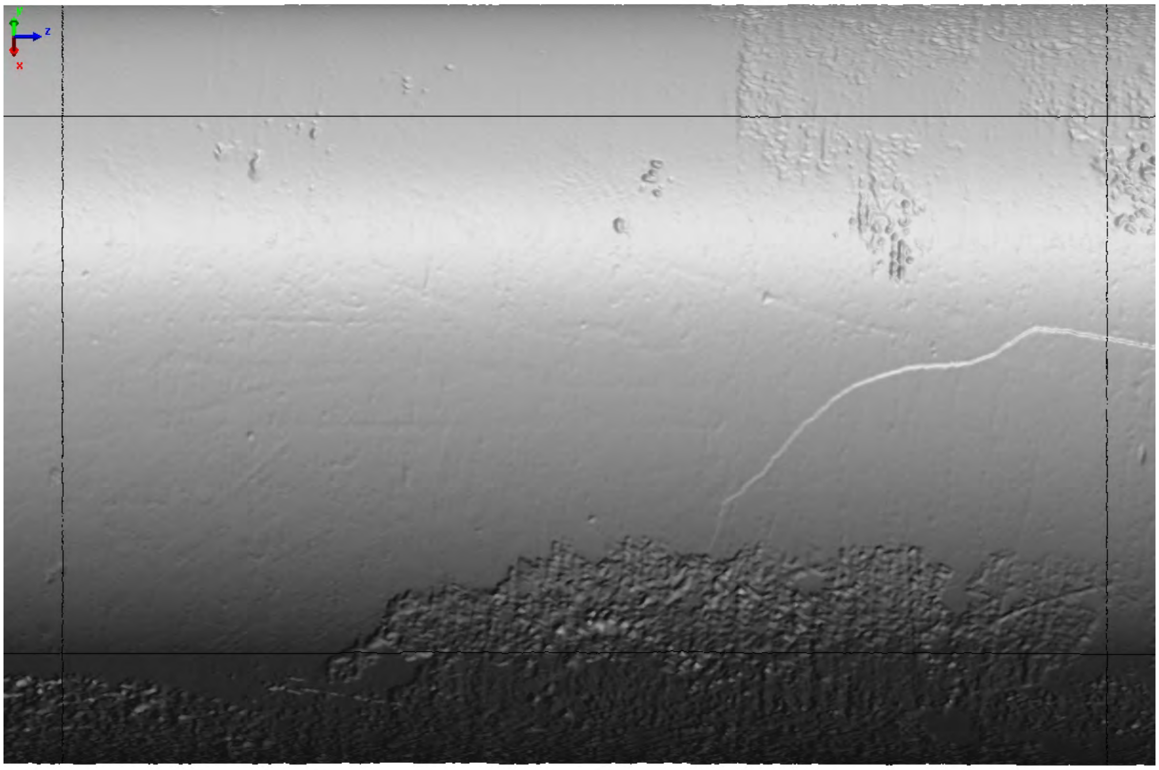


Figure A-145(9). 6-9 feet and 0-90 degrees



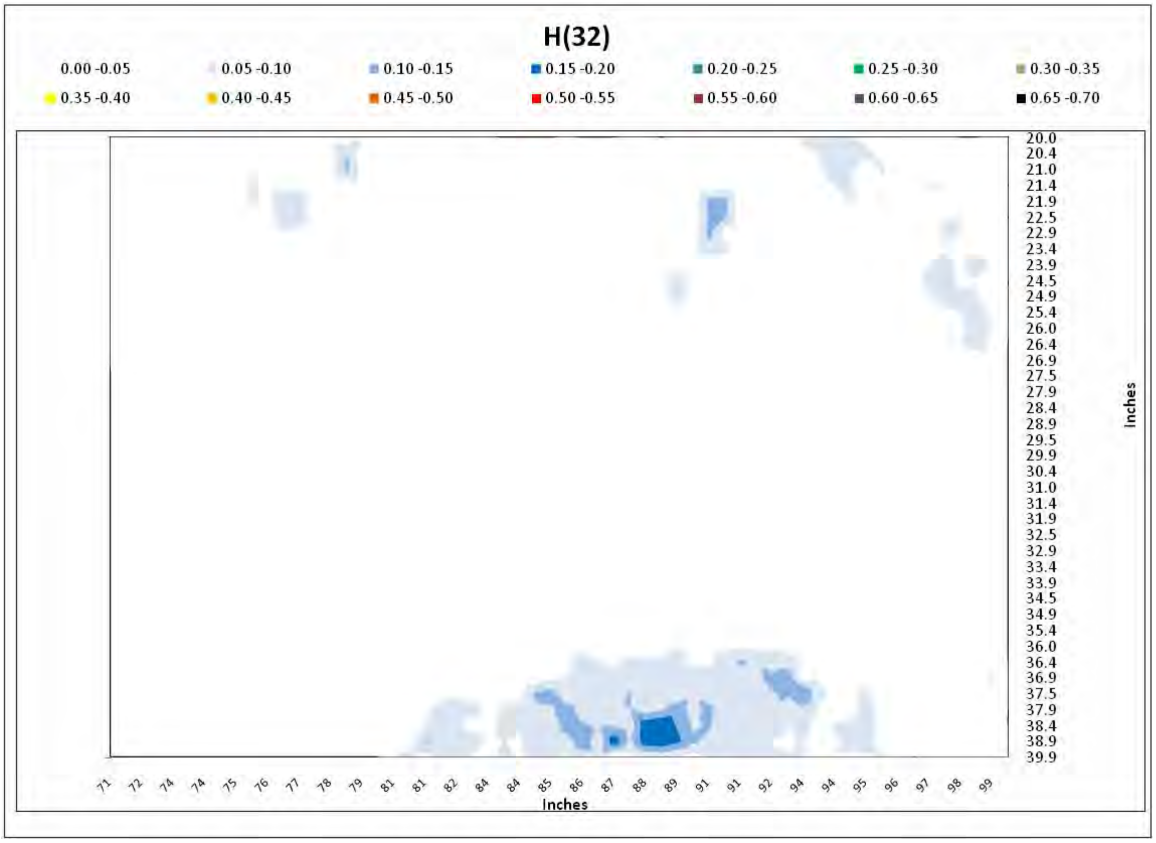


**Figure A-145(10). 6-9 feet and 90-180 degrees**

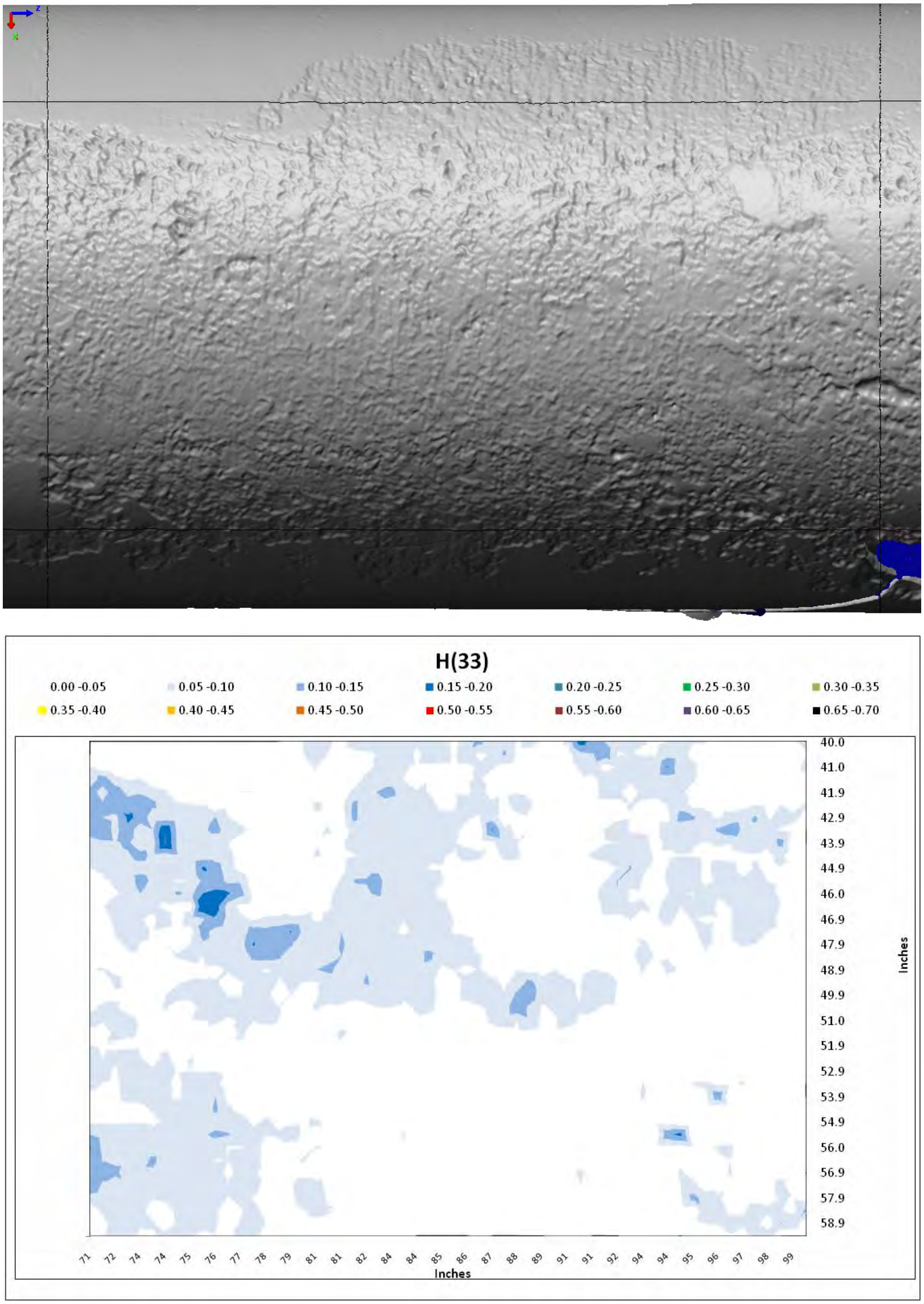


Figure A-145(11). 6-9 feet and 180-270 degrees

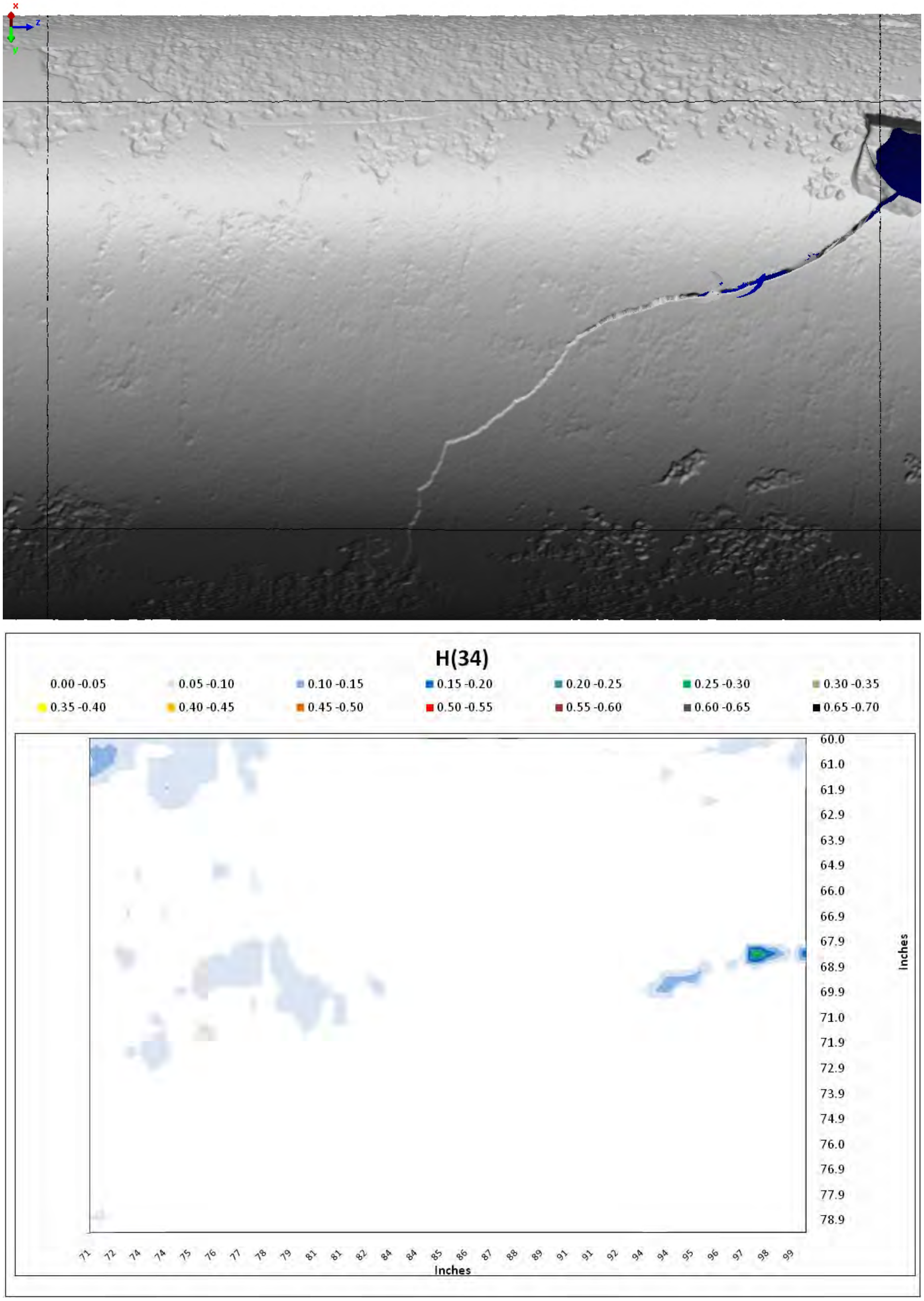


Figure A-145(12). 6-9 feet and 270-300 degrees

Figure A-146(1). Pipe 146 as Removed from Site

Figure A-146(2). Pipe 146 after Sandblasting

Note that Pipe 146 was a cutout and not a complete pipe. Therefore, only partial measurements were made and are presented next.

**Table A-146(1). Scanned Pipe 146 Summary Table**

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Spigot (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| H11 | 4.3 | 19.4 | 0.1185 | 16% | 0.6445 | 84% | 84 | 2:48 |
| H12 | 17.3 | 24.4 | 0.1732 | 23% | 0.5898 | 77% | 149 | 4:57 |
| H13 | 9.1 | 29.8 | 0.2367 | 31% | 0.5263 | 69% | 191 | 6:22 |
| | | 28.9 | 0.1618 | 21% | 0.6012 | 79% | 180 | 5:59 |
| H14 | 20.3 | 2.0 | 0.4024 | 53% | 0.3606 | 47% | 273 | 9:05 |
| | | 9.8 | 0.4185 | 55% | 0.3445 | 45% | 271 | 9:01 |
| | | 17.4 | 0.2858 | 37% | 0.4772 | 63% | 269 | 8:57 |
| | | 18.9 | 0.4126 | 54% | 0.3504 | 46% | 269 | 8:57 |
| | | 10.9 | 0.2394 | 31% | 0.5236 | 69% | 311 | 10:21 |
| | | 18.9 | 0.2429 | 32% | 0.5201 | 68% | 326 | 10:52 |
| | | 25.9 | 0.2244 | 29% | 0.5386 | 71% | 331 | 11:01 |
| | | 30.4 | 0.2591 | 34% | 0.5039 | 66% | 328 | 10:56 |
| H21 | 1.9 | 55.5 | 0.1713 | 21% | 0.6327 | 79% | 89 | 2:57 |
| H22 | 16.0 | 49.0 | 0.2681 | 33% | 0.5359 | 67% | 155 | 5:10 |
| | | 51.0 | 0.2984 | 37% | 0.5056 | 63% | 155 | 5:10 |
| | | 50.0 | 0.2539 | 32% | 0.5501 | 68% | 144 | 4:48 |
| | | 47.5 | 0.2173 | 27% | 0.5867 | 73% | 138 | 4:35 |
| | | 56.0 | 0.2236 | 28% | 0.5804 | 72% | 157 | 5:14 |
| H23 | 12.5 | 55.0 | 0.1461 | 18% | 0.6579 | 82% | 206 | 6:52 |
| H24 | 7.2 | 38.5 | 0.1902 | 24% | 0.6138 | 76% | 313 | 10:26 |
| | | 37.1 | 0.1878 | 23% | 0.6162 | 77% | 335 | 11:10 |

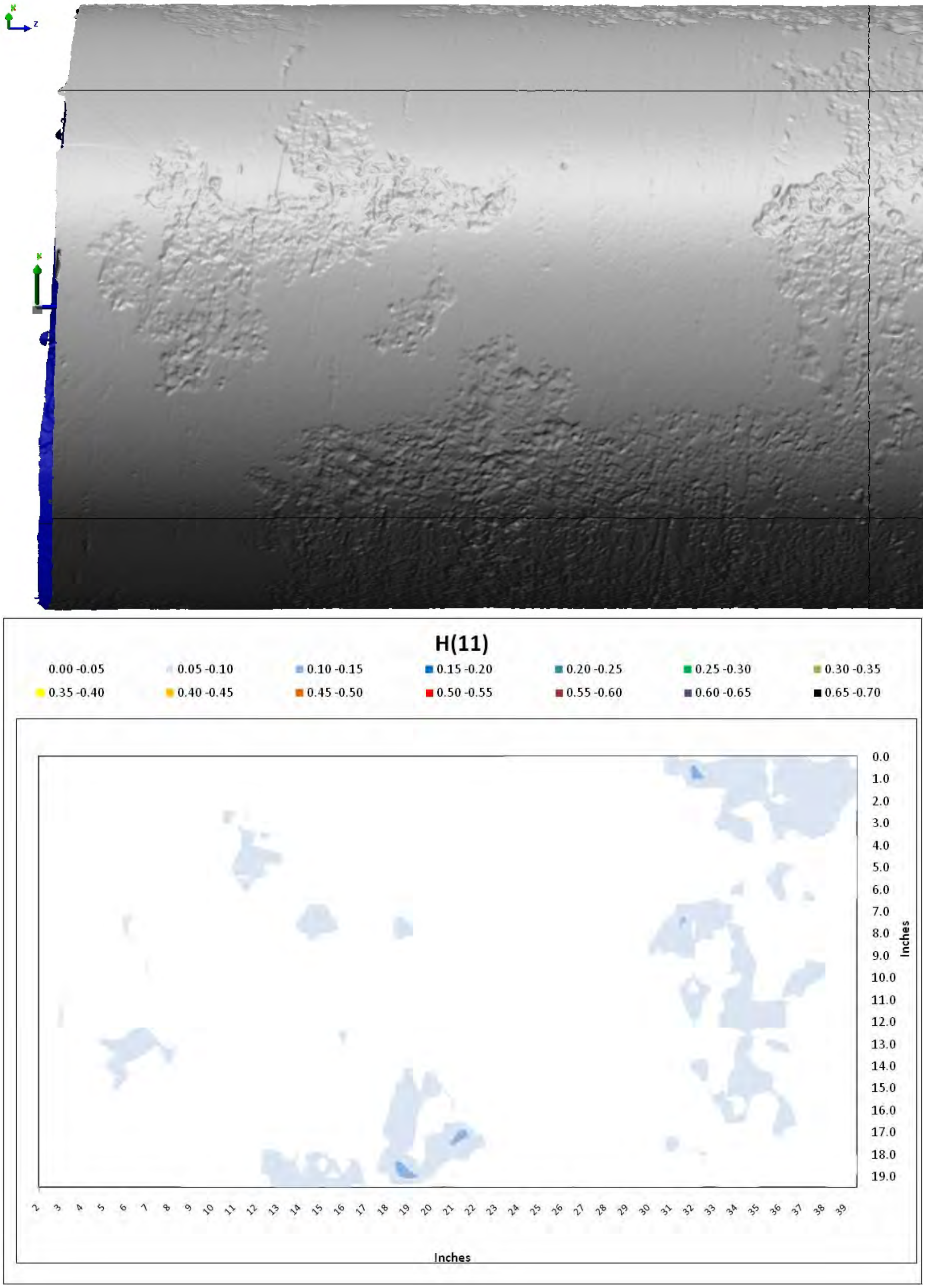


Figure A-146(1). 0-3 feet and 0-90 degrees

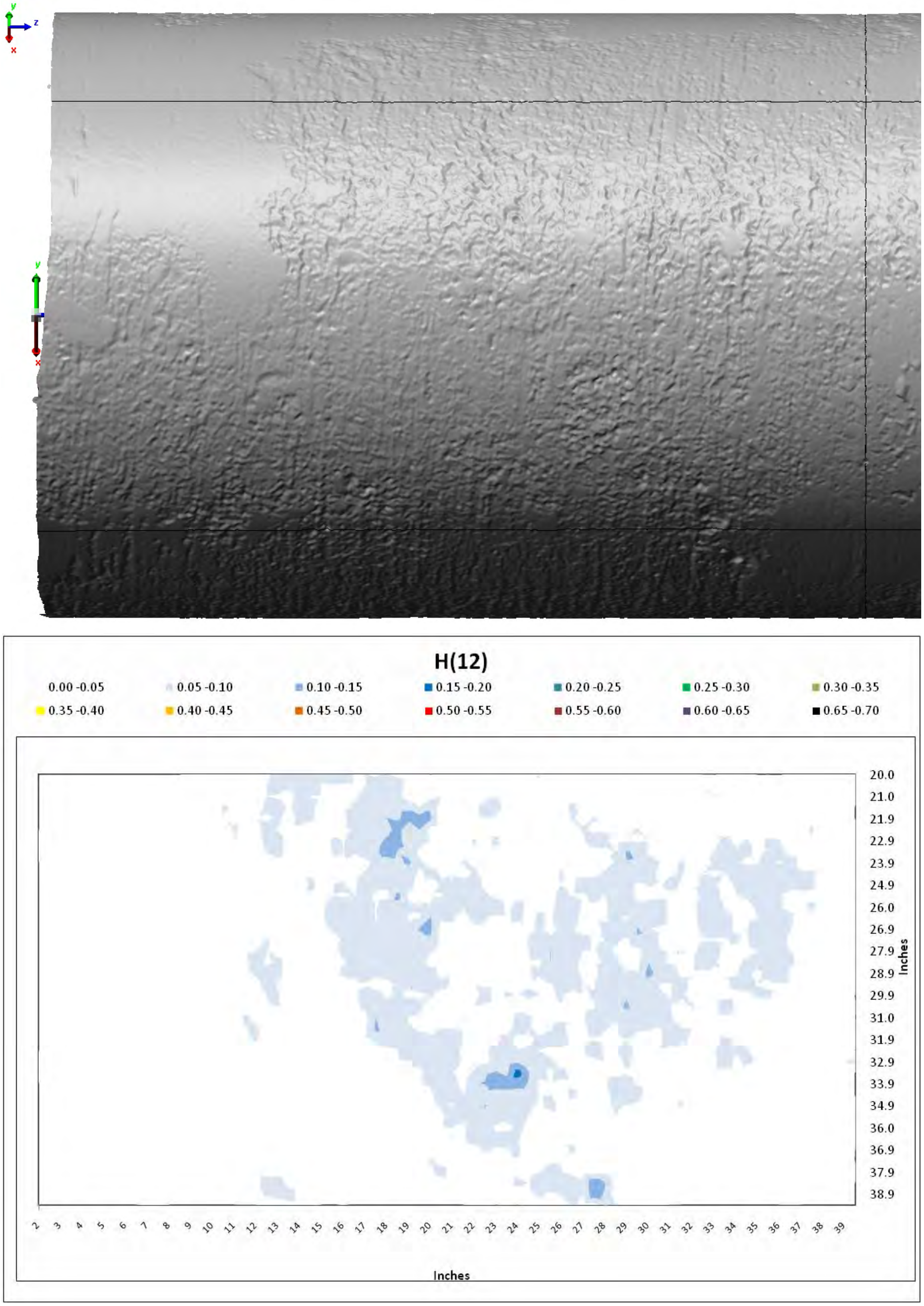


Figure A-146(2). 0-3 feet and 90-180 degrees

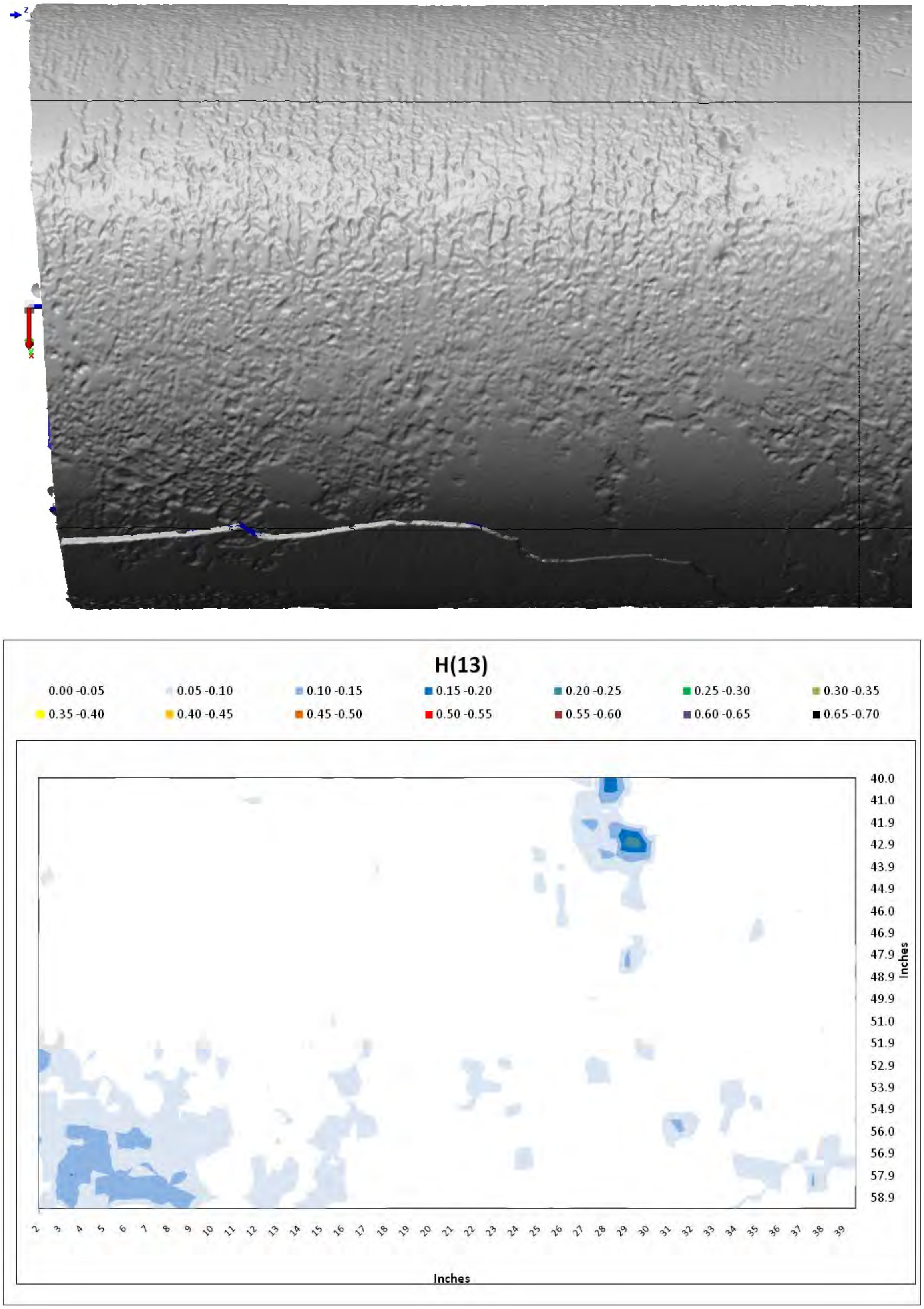


Figure A-146(3). 0-3 feet and 180-270 degrees

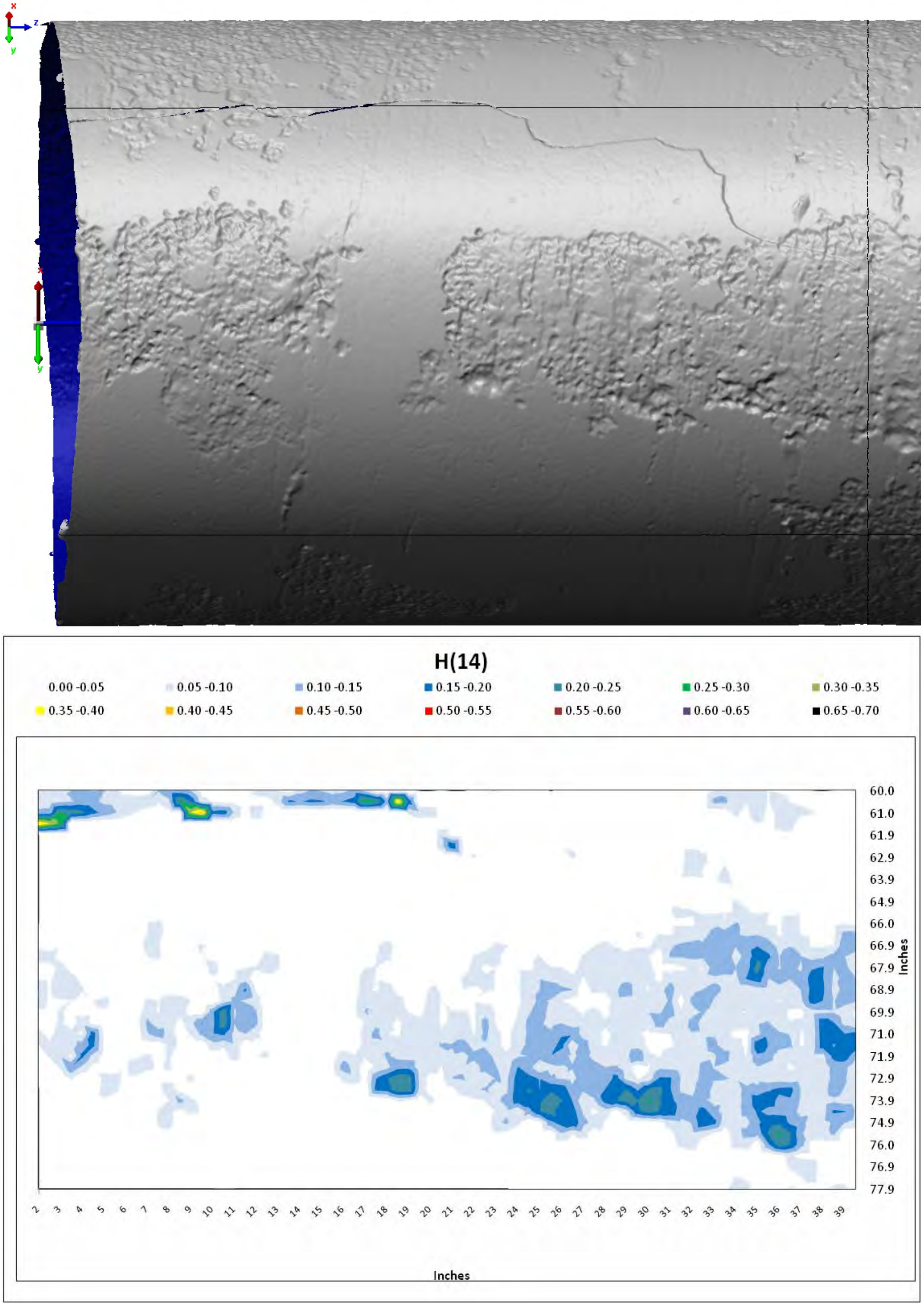


**Figure A-146(4). 0-3 feet and 270-300 degrees**

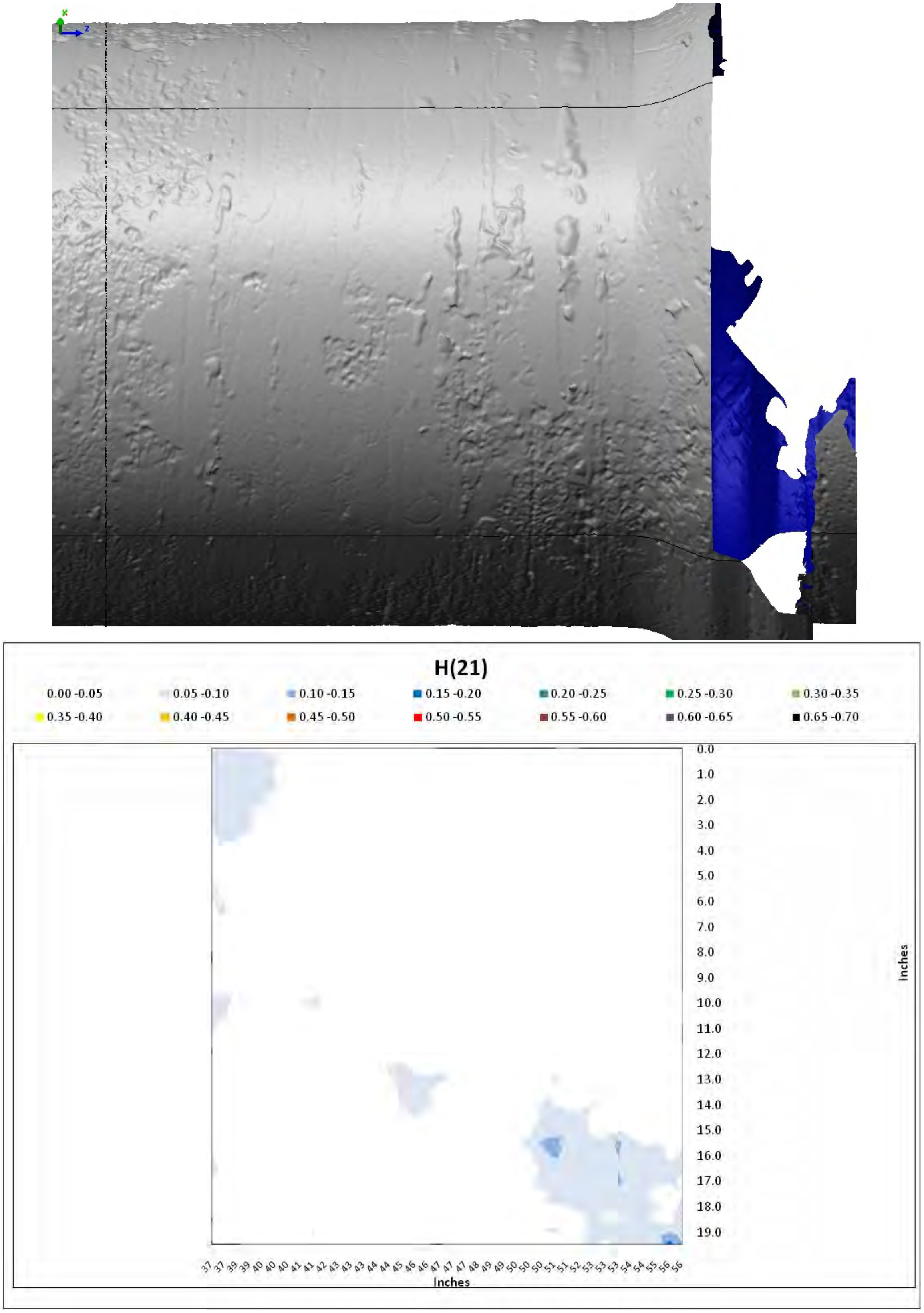


**Figure A-146(5). 3-6 feet and 0-90 degrees**

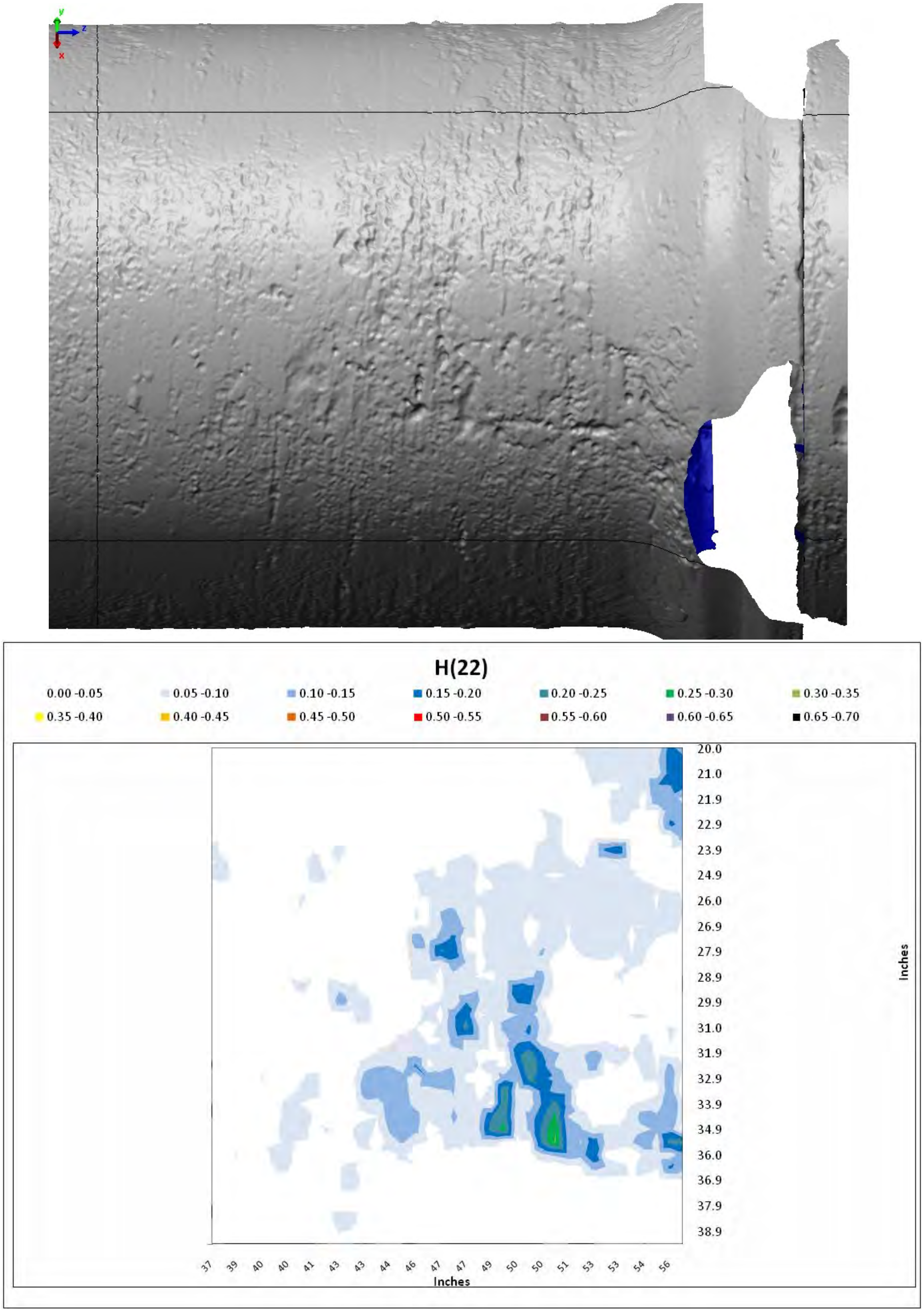


Figure A-146(6). 3-6 feet and 90-180 degrees

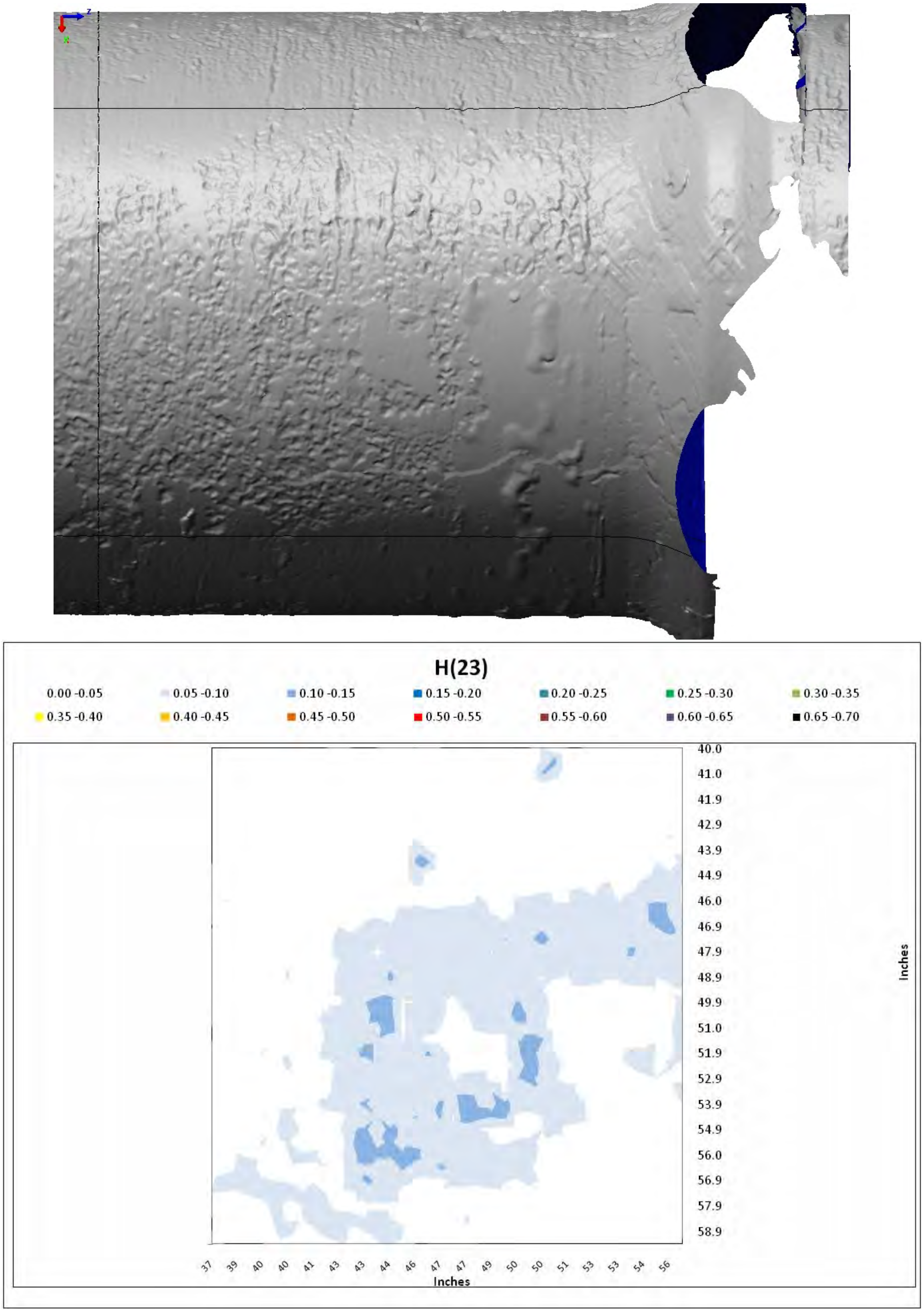


Figure A-146(7). 3-6 feet and 180-270 degrees

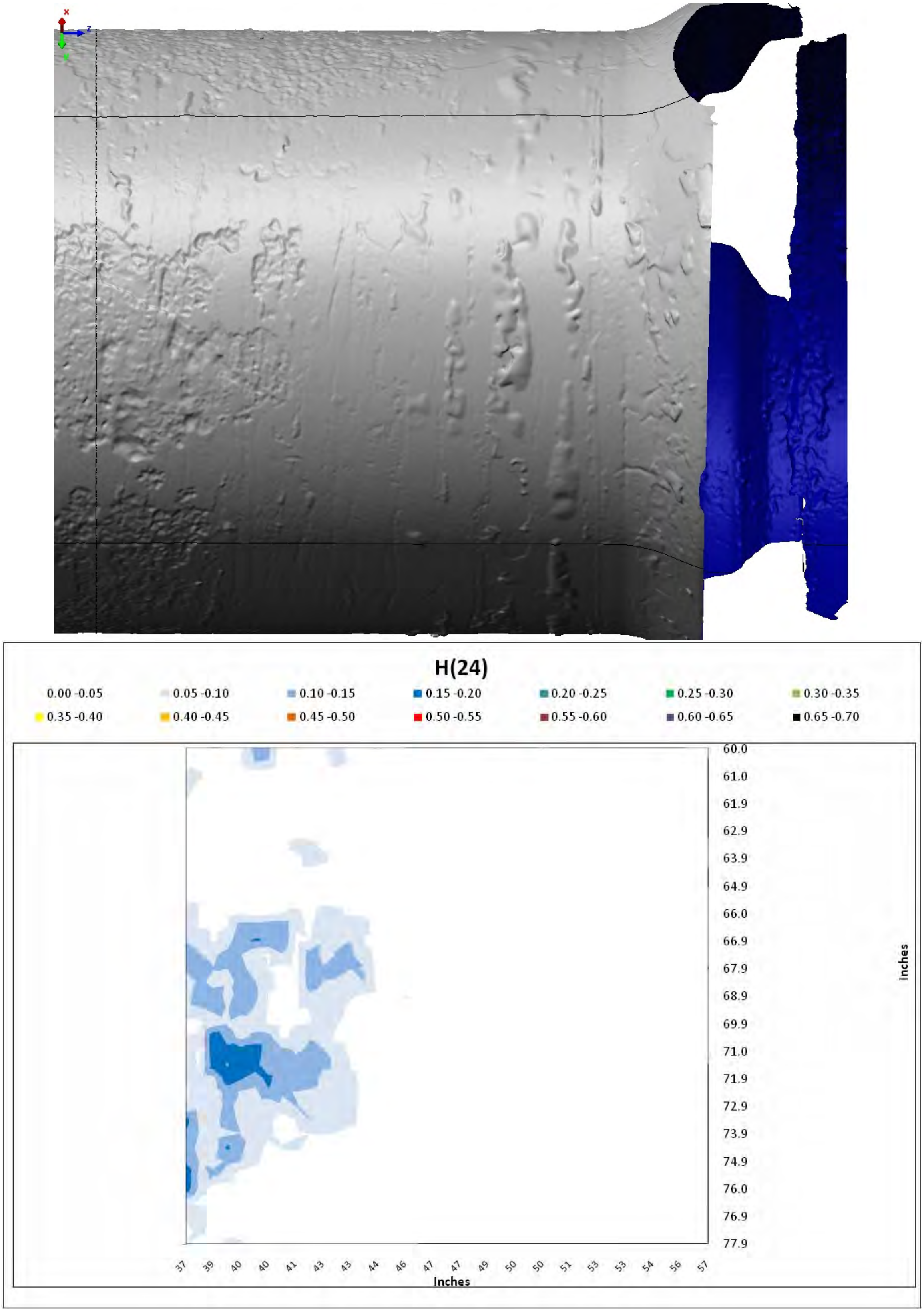


Figure A-146(8). 3-6 feet and 270-300 degrees

Figure A-166(1).  Pipe 166 as Removed from Site

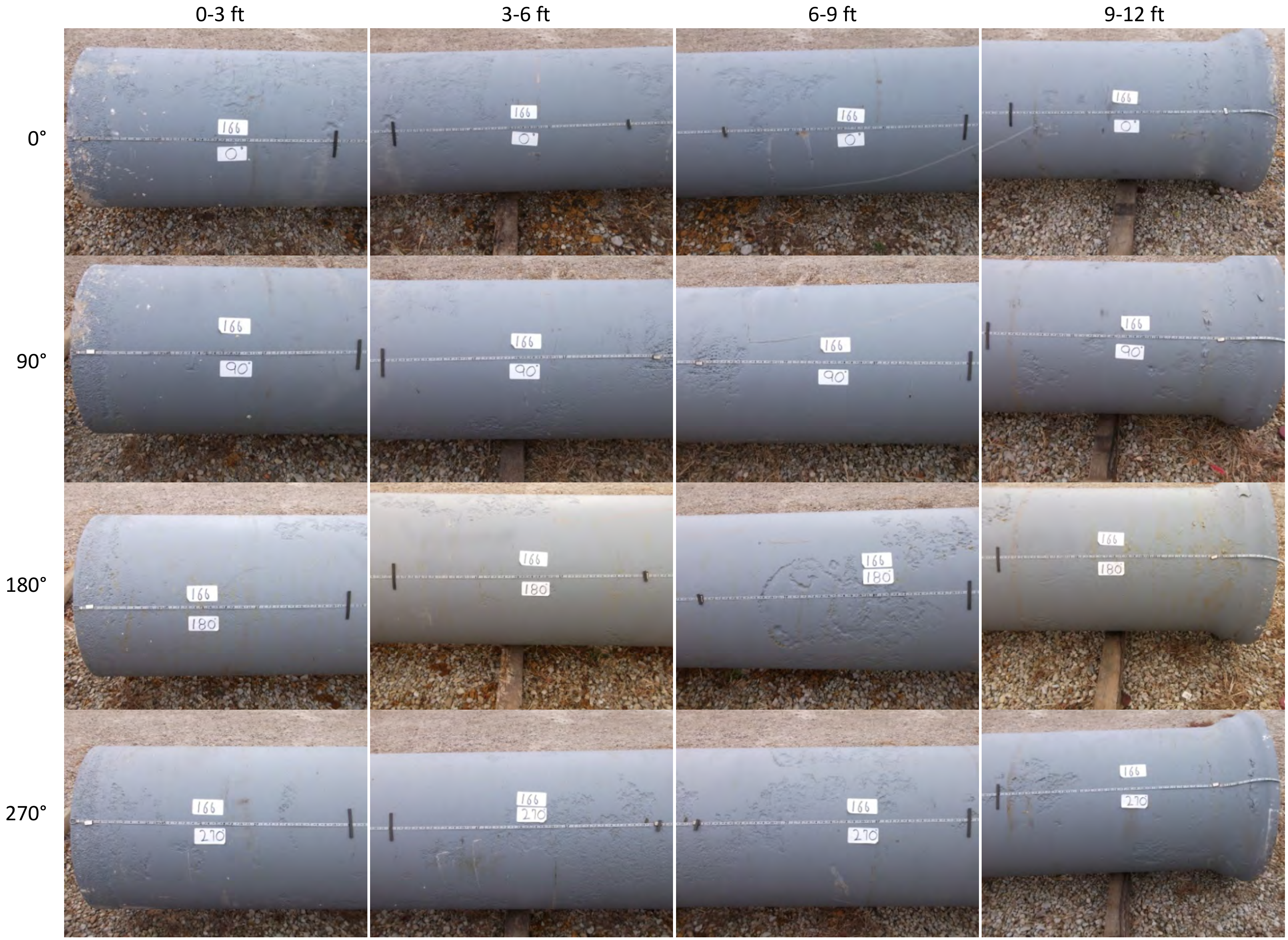


Figure A-166(2). Pipe 166 after Sandblasting

### Table A-166(1). Wall Thickness of Cast Iron at Spigot with Caliper

| Pipe Number | Wall Thickness (inches) | | | |
|---|---|---|---|---|
| | 75° | 150° | 180° | 270° |
| 166 | 0.829 | 0.834 | 0.833 | 0.842 |

### Table A-166(2). Wall Thickness Cast Iron Using an Ultrasonic Gauge (inches)

| Pipe Number | Wall Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spigot | | | | Center | | | Bell | | |
| | Caliper | UT | | | UT | | | UT | | |
| 166 | 0.832 | 0.814 | 0.815 | 0.819 | 0.830 | 0.834 | 0.831 | 0.781 | 0.769 | 0.788 |
| | 0.830 | 0.822 | 0.819 | 0.816 | 0.832 | 0.822 | 0.828 | 0.776 | 0.793 | 0.812 |
| | 0.836 | 0.808 | 0.819 | 0.820 | 0.827 | 0.829 | 0.831 | 0.791 | 0.804 | 0.798 |
| **Average** | 0.833 | 0.817 | | | 0.829 | | | 0.790 | | |
| **Standard Deviation** | 0.003 | 0.004 | | | 0.003 | | | 0.014 | | |
| **Minimum** | 0.830 | 0.808 | | | 0.822 | | | 0.769 | | |
| **Maximum** | 0.836 | 0.822 | | | 0.834 | | | 0.812 | | |
| **Repeat Center Cell** | - | 0.814 | | | 0.828 | | | 0.790 | | |

### Table A-166(3). Outer Diameter Measurement Using a pi Tape

| Pipe Number | Outer Diameter | | |
|---|---|---|---|
| | Spigot | Center | Bell |
| 166 | 25.900 | 25.800 | 25.792 |

### Table A-166(4). Wall Thickness of Cement Liner at Spigot with Caliper

| Measurement (Inches) | 75° | 150° | 180° | 270° |
|---|---|---|---|---|
| **Cast Iron** | 0.829 | 0.834 | 0.833 | 0.842 |
| **Cast Iron & Cement Liner** | 1.152 | 1.078 | 1.056 | 1.015 |
| **Cement Liner** | 0.323 | 0.244 | 0.223 | 0.173 |

### Table A-166(5). Pipe 166 Summary Table

| Defect Area | Total Volume Loss (in.$^3$) | Dist From Bell (in.) | Maximum Depths In Defect Area (in.) | % Loss | Remaining (in.) | % Remaining | Clock (Degrees) | Clock (12hr) |
|---|---|---|---|---|---|---|---|---|
| 166-095-113-015-043 | 5.5 | 45.0 | 0.260 | 33% | 0.52 | 67% | 211 | 7:02 |
| | | 43.0 | 0.223 | 29% | 0.56 | 71% | 216 | 7:12 |
| 166-080-156-026-055 | 12.6 | 67.5 | 0.291 | 37% | 0.49 | 63% | 162 | 5:24 |
| | | 68.5 | 0.246 | 31% | 0.53 | 69% | 155 | 5:10 |
| | | 65.0 | 0.206 | 26% | 0.57 | 74% | 151 | 5:02 |
| 166-026-092-038-058 | 9.5 | 111.0 | 0.256 | 33% | 0.52 | 67% | 228 | 7:36 |
| | | 101.5 | 0.196 | 25% | 0.58 | 75% | 230 | 7:40 |
| | | 101.5 | 0.189 | 24% | 0.59 | 76% | 248 | 8:16 |
| | | 113.0 | 0.166 | 21% | 0.61 | 79% | 237 | 7:54 |

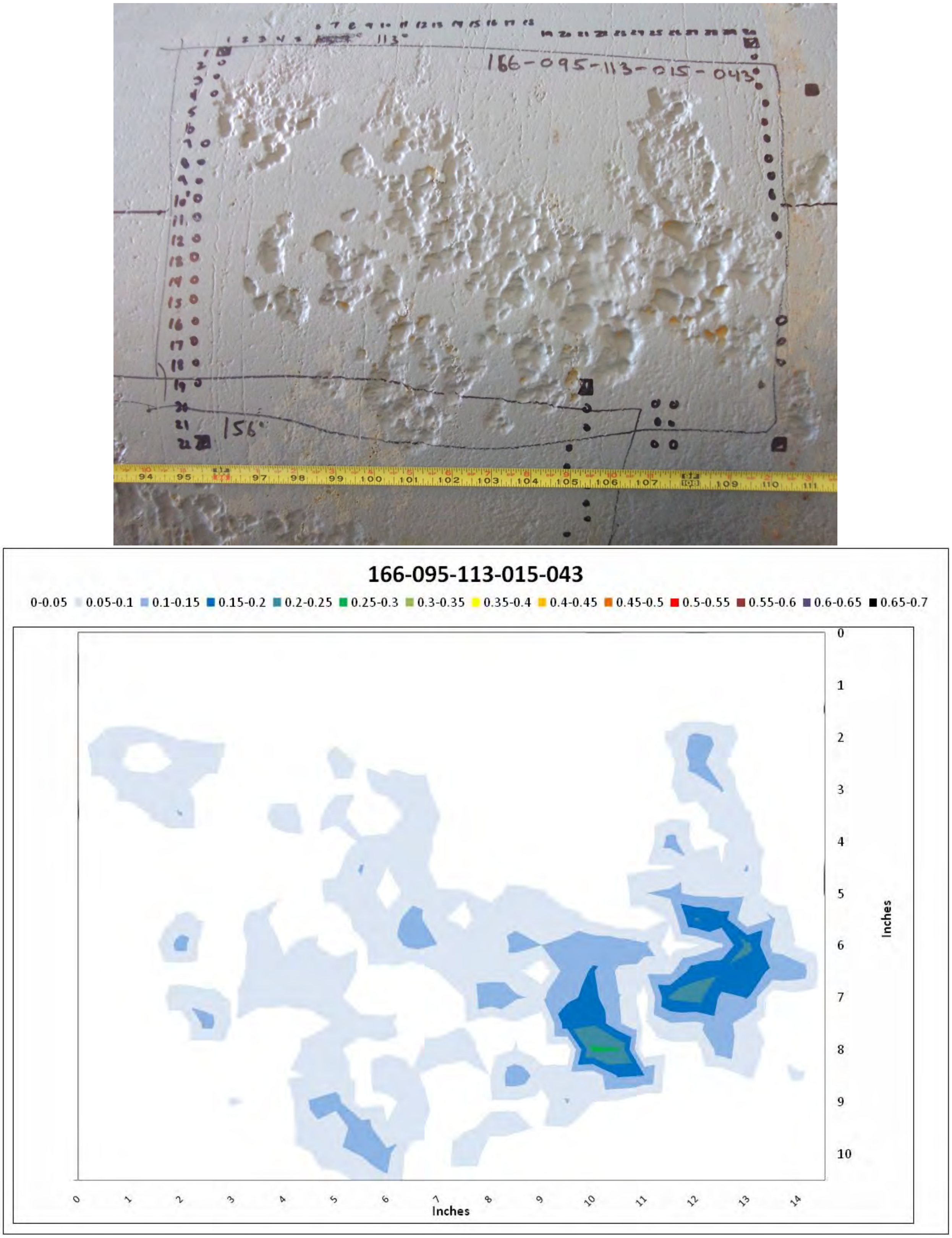


Figure A-166(1). Pipe 166, area 166-095-113-015-043

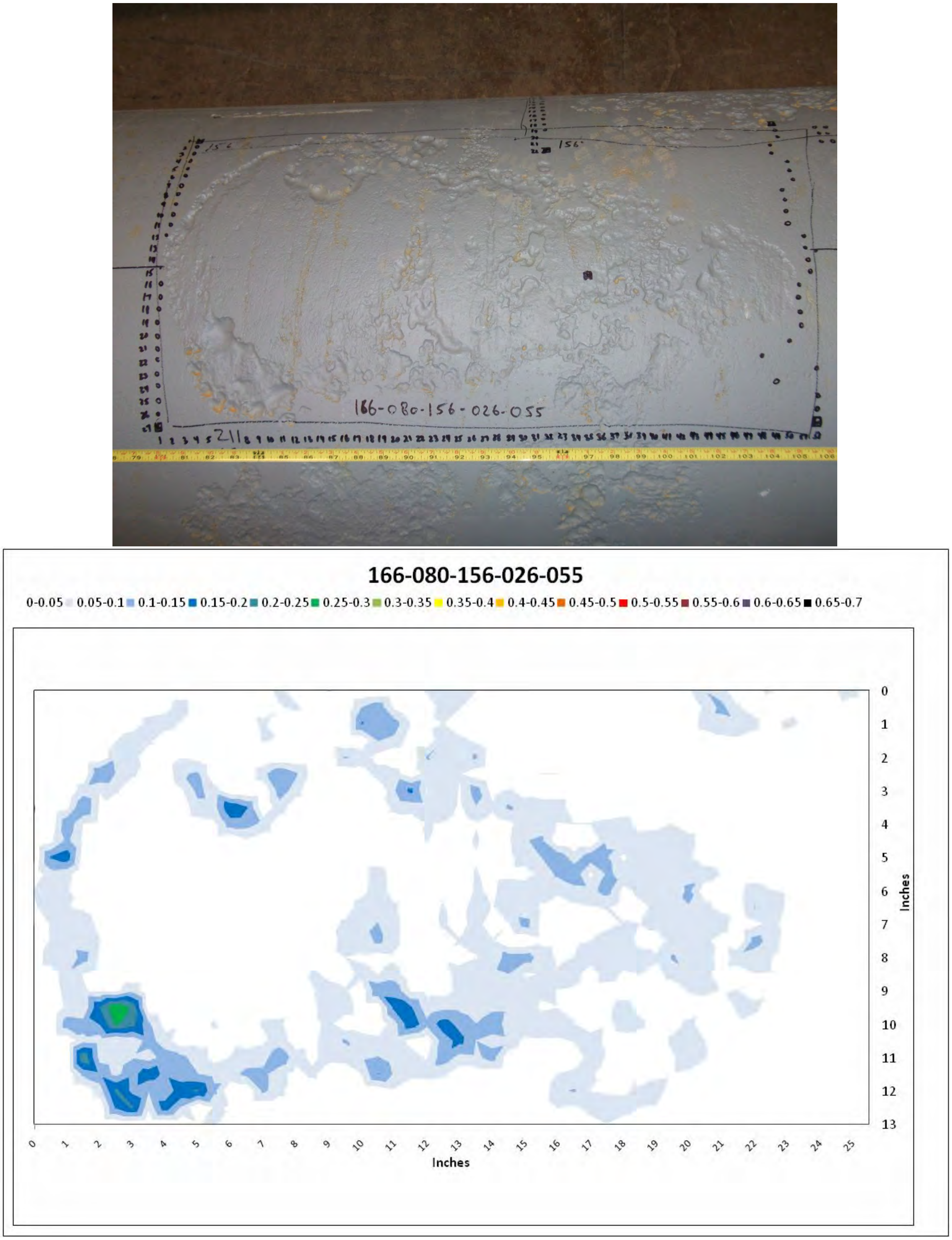


Figure A-166(2). Pipe 166, area 166-080-156-026-055

Appendix B

PPIC
the Pressure Pipe
Inspection Company

# FIELD DEMONSTRATION OF NONDESTRUCTIVE PIPELINE CONDITION ASSESSMENT OF METALLIC WATER PIPE USING SAHARA™ LEAK DETECTION/ VIDEO/ WALL THICKNESS TESTING & PIPEDIVER™ RFEC TESTING

JULY 2009

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# 1. EXECUTIVE SUMMARY

Over the course of July 13th to 29th, 2009, the Pressure Pipe Inspection Company (PPIC) performed non-destructive condition assessment of a cast iron main using two non-disruptive inspection platforms, Sahara and PipeDiver. The assessment was conducted on a 2057 foot long, 24 inch diameter, cast iron section of the Westport Rd. Transmission Main between Pit 1 (Launch/Insertion Pit) and Pit 3 (Receive/Extraction Pit).

PPIC used its patented Sahara Technology, including Sahara Leak Detection, Sahara Video, and Sahara Wall Thickness Testing. In addition, PPIC conducted a Remote Field Eddy Current (RFEC) pilot test for metallic pipe wall condition assessment using the PipeDiver inspection platform. Both technologies are non-disruptive and allow the pipeline to remain in service during the inspection. PPIC's inspections are part of a study conducted by the U.S. Environment Protection Agency (EPA).

Sahara Leak Detection identified six natural leaks and an air pocket within the inspected area and detected all simulated leaks. Sahara Video identified several corrosion spots, outlets, and air pockets within the pipeline. Analysis of the Sahara Wall Thickness Testing data revealed several areas of suspected wall thickness loss. PipeDiver RFEC testing was performed over the full scope (2057 ft) under live conditions and identified 41 pipe sections with anomalous data signals. Verification and further calibration are recommended to confirm the exact nature of these anomalies and help in further refinement of the PipeDiver analysis procedures. Each individual technology provides a particular service but their combined results provide a complete overall condition assessment of the pipeline.

# 2. PROJECT BACKGROUND

## 2.1 Project Background

The U.S. Environmental Protection Agency (EPA) contracted the Battelle Memorial Institute (BMI) to demonstrate selected innovative leak detection/location and structural condition assessment technologies. This study emphasizes the need for non-invasive, non-destructive, "inexpensive" techniques to help utilities assess the condition of their lines to allow them to make good decisions regarding capital replacements, rehabilitation or monitoring of their pipe infrastructure.

The Pressure Pipe Inspection Company (PPIC) is one of the several companies contracted by BMI to demonstrate their non-destructive condition assessment techniques of metallic pipes. These include PPIC's patented Sahara Leak Detection, Sahara Video, Sahara Wall Thickness Testing and PipeDiver RFEC Testing. All these technologies are invasive, requiring internal pipe access, but are non-disruptive in nature and are performed while the pipeline is in service. Each technology has its own set of advantages and limitations which allows utilities an option on which inspection technique best fits their needs and expectations. Additionally, multiple techniques can be applied to a single pipeline to provide successive levels of detail about the pipe condition.

The condition assessment technologies deployed by PPIC are at various stages of commercial deployment. The Sahara leak detection system, for example, has been successfully used commercially worldwide for over 10 years.  While PipeDiver has been successfully used in PCCP for live condition assessment, PipeDiver RFEC for metallic pipes is still undergoing development and in the process of becoming a commercially available service.

The Westport Rd. Transmission Main is a 24 inch diameter cast iron pipe that has been taken out of service. EPA has acquired this pipeline for a non-destructive condition assessment study, which PPIC is a part of. A map showing the approximate location of the inspected pipeline is shown in Figure 2.1.

**Figure 2.1 Pipeline Plan**

Additional features were created along the inspection scope for various test procedures. These features are listed in Table 2.1 (distances provided by the Battelle Memorial Institute).

**Table 2.1 Feature List**

| Feature | Distance from Pit 1 (ft) | STA |
|---|---|---|
| Pit 1 (Launch/Insertion Pit) | 0 | 160+55 |
| Pit A | 250 | 163+05 |
| Pit B | 510 | 165+65 |
| Pit 4 | 581 | 166+36 |
| Pit C | 809 | 168+64 |
| Pit 2 | 1080 | 171+35 |
| Pit D | 1173 | 172+28 |
| Pit E | 1439 | 174+94 |
| Pit 5 | 1580 | 176+35 |
| Pit F | 1750 | 178+05* |
| Pit 3 (Receive/Extraction Pit) | 2057 | 181+12 |

*STAs are in relation to fire hydrant STA of 178+05 and distances from Pit 1 (hydrant listed in same location as Pit F from Battelle chart).

## 2.2 Purpose of Inspection

The purpose of this inspection is to demonstrate PPIC's various non-destructive condition assessment services on metallic pipe which, together, provide an overall condition assessment of the pipeline. These services include:

- A visual inspection of the inside of the pipeline
- Identifying and quantifying the presence of leaks
- A pipe wall assessment including wall thickness loss and irregularities

All services are performed using PPIC's patented Sahara technology platform and the PipeDiver platform, both of which are live inspection platforms that operate while the pipeline is in service.

## 2.3 Test Pipe Line Description

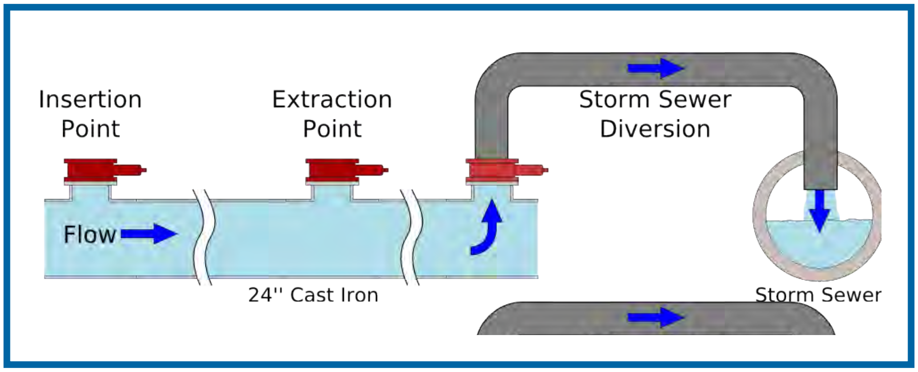
The non-destructive condition assessment inspections of the Westport Rd. Transmission Main were conducted from July 13th to 29th, 2009. The test details are summarized in Table 2.2.

**Table 2.2 Test Summary**

| | |
|---|---|
| **Pipeline** | Westport Rd. Transmission Main |
| **Inspection Dates** | July 13th to 29th, 2009 |
| **Total Distance** | 2057 feet |

In order to produce sufficient flow in the pipeline for inspection purposes a 12 inch tee past the extraction point was used to temporarily create flow by diverting water into a nearby storm drain.

**Figure 2.2 Pipeline Flow Setup**



The flow amount and duration was limited by the capacity of the storm sewer. In the event of rain, the storm sewer's capacity would be reduced or eliminated entirely which, in turn, would likewise affect the flow available in the 24 inch cast iron line.

## 3. SAHARA TECHNOLOGY

### 3.1 Background and Theory

#### 3.1.1 Sahara Platform

The first tool designed for live inspection of large diameter water mains, the Sahara Pipeline Inspection System, is capable of detecting leaks, pockets of trapped gas, and structural defects in large mains. Sahara is a critical component of condition assessment and water loss management programs for utilities around the world. The unique Sahara platform allows adaption of multiple technologies such as leak detection, video inspection, and wall thickness assessment.

Advantages to the Sahara inspection system include:

- No disruption to pipeline service
- Use existing 2 inch (50 mm) taps
- A tethered system allows complete control of the sensor's position along the pipe and ensures no lost sensors
- Accurate surface tracking to map pipelines and leak locations
- Usable in mains of all material types, as small as 4 inches in diameter, and with pressures up to 200 PSI

### 3.1.2 Sahara Leak Detection

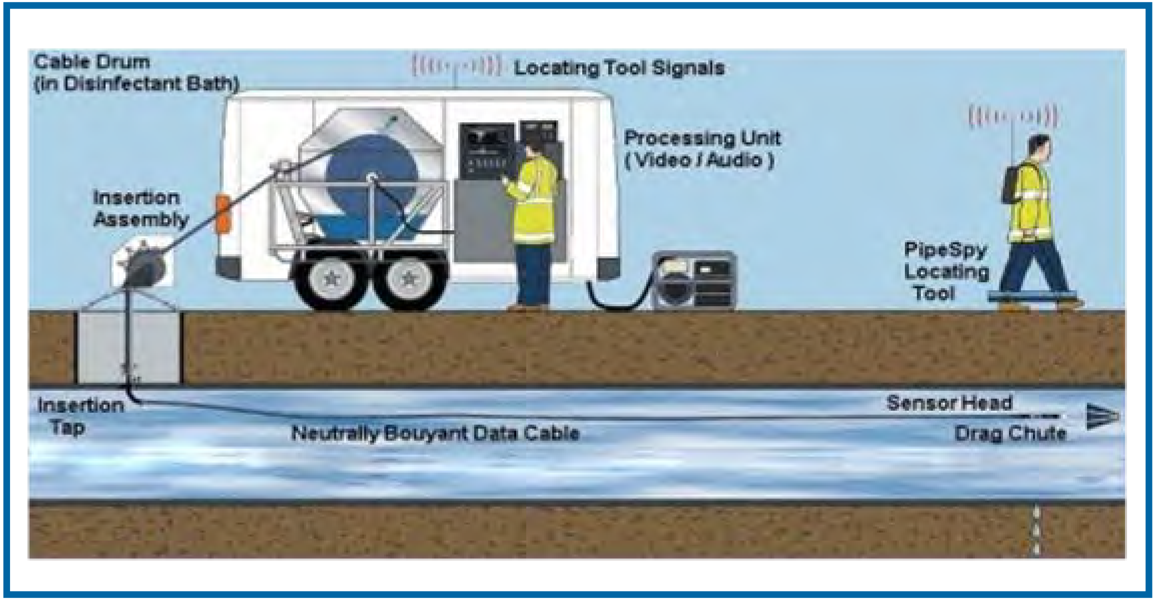
The Sahara system is a non-destructive condition assessment technology that pinpoints the location and estimates the magnitude of leaks in large diameter, 12 inch and above, water transmission mains of all construction types. With over 1,000 miles (1,600 km) of inspections Sahara Leak Detection has proven sensitive to leaks as small as 0.005 gal/min (located in 72" PCCP at 87 psi). Leaks are located above ground in real-time and marked to within 1 foot of accuracy.

In operation, the system is inserted into a live pipeline through any tap that is at least 2 inches in diameter. Carried by the flow of water, the tethered sensor head can then travel through the pipe for distances up to 6,000 feet per survey detecting each leak as it is found. The leak's position is then located and marked on the above ground surface facilitating subsequent repairs.

An electronics processing unit with audio and visual output is used for data analysis. A leak produces a distinctive acoustic signal which is recorded by the sensor and processed into a visual signal. The visual signal is then analyzed along with the audio signal to quantify the leak.

In no flow situations a second tethering line (mule tape) can be used to pull the hydrophone through a pipeline.

**Figure 3.1 Sahara Inspection System**

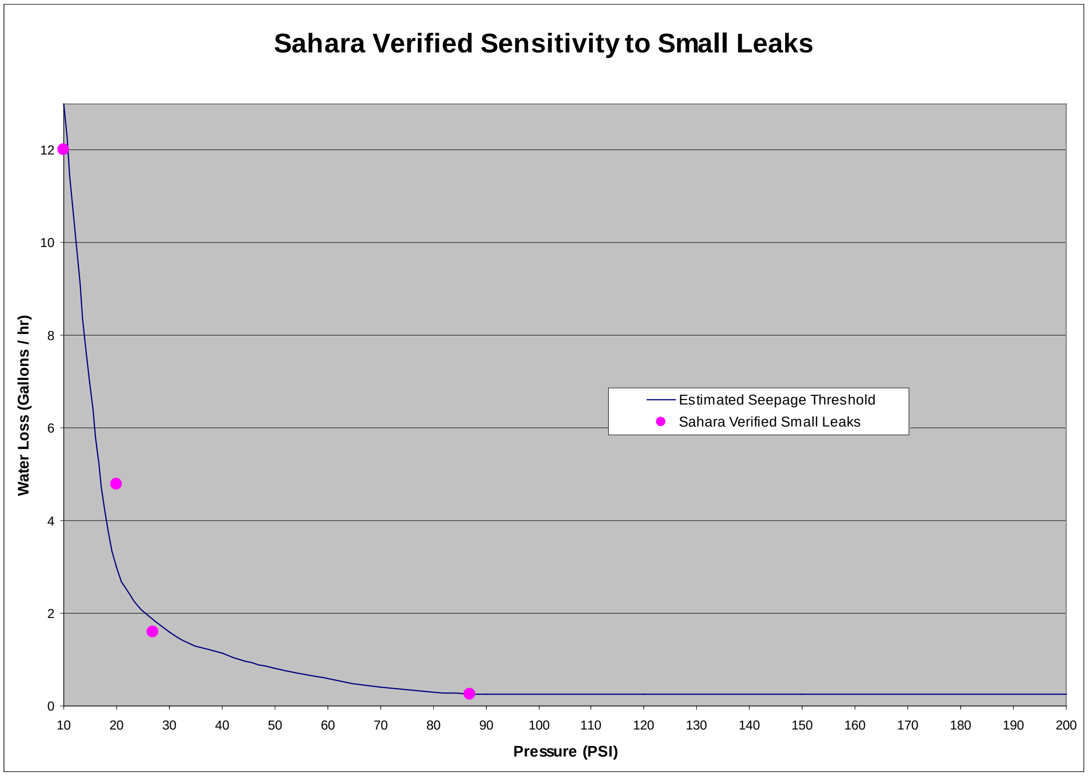


An operator stands by at the controller station to control hydrophone deployment and listen to the hydrophone signal for leaks in real time. Once a leak is detected the hydrophone can pass over the leak multiple times to classify and pinpoint the leak. A second operator travels the pipeline above ground using a tool to detect the exact location of the sensor. When a leak is detected this operator will make a mark on the ground identifying the location and record a GPS point for reference.

The capable survey length of the Sahara system is limited not only by the amount of available cable, usually 1.2 miles (2 km), but also by the pipeline geometry (horizontal/vertical elbows and bends), the pipeline flow rate, and the internal pipe conditions.

Sahara Leak Detection is a proven technique in identifying the smallest leaks in pipelines. Figure 3.2 below depicts some verified leaks and the corresponding pressures the leaks were detected at.

**Figure 3.2 Sahara Verified Leaks**



Calibration is performed by testing each hydrophone and comparing it to a standard frequency response. The Sahara hydrophone has sensitivity to leaks as small as 0.005 gal/min (detected on 48” PCCP pipeline at 87 psi).

Data is interpreted and analyzed in real time by on screen spectrogram and audio listening. Using dual analysis methods provides high accuracy and can clearly distinguish leaks from ambient noise.

Factors such as low water pressure, electrical noise, air pockets, and external ambient noise can all affect the real time analysis of the sensor signal. During the inspection, some leaks were masked by external factors and required post analysis to detect the leaks.

### 3.1.3 Sahara Video Description

Sahara Video provides real time, in-service CCTV inspection through a 2 inch or larger tap. Real-time video inspection enables visual inspection of features including:

- Cement and other liners
- Internal corrosion and tuberculation assessments
- Valve location and inspection
- Debris and blockages

The Sahara video system utilizes the same control system and tethered cable as the Sahara Leak Detection system but the hydrophone sensor head is switched to a video camera head that traverses a pipeline after begin inserted through a standard 2 inch tap. A drogue (parachute) is attached just behind the camera which captures water flow and carries the camera and cable down the pipeline.

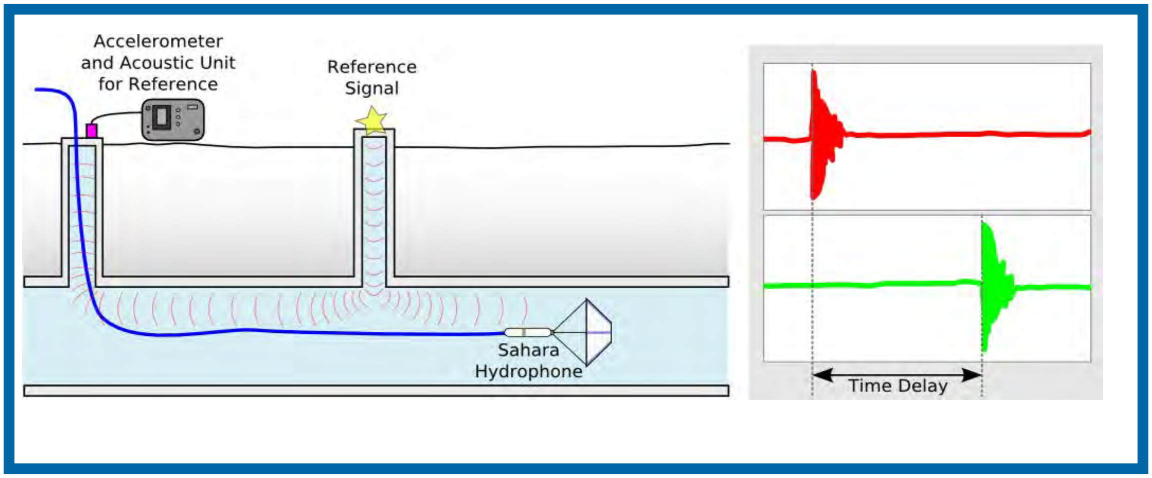
An operator stands by at the controller station to control camera deployment and views the video output in real time. A second operator traverses the pipeline above ground using a tool to detect the exact location of the camera. When an item of interest is seen the second operator will make a mark on the ground identifying the location and record a GPS point for reference.

Like the Sahara leak detection, the Sahara video system has a limited survey length from the pipeline configuration and available flow rate. One circumstance or factor affecting accuracy is video clarity. Video image becomes less clear in larger diameter pipes, due to diffuse lighting and reduced field of view, and unclear water. To calibrate the video system, each video camera is tested and compared to a standard frequency response. Video is interpreted and analyzed in real time, but also recorded for future examination.

### 3.1.4 Sahara Wall Thickness Testing

Sahara Wall Thickness Testing can be performed in conjunction with a Sahara Leak Detection inspection. Testing requires a secondary acoustic sensor, either an external accelerometer attached to the pipe surface or an additional internal hydrophone. Reference signals (e.g., test strikes at access points or sounds produced by a speaker) are generated within the pipe for testing.

The sound waves propagate through the pipeline in a specific manner bouncing repeatedly off of the pipe walls. As the sound wave travels in this manner they gather information about the pipe wall. By measuring the speed of sound multiple times in a section of pipe the average wall thickness can be deduced. By using multiple acoustic sensors separated by a known distance time of arrival data from the reference signal can be used to calculate the speed of sound within the pipe and thus the average wall thickness.



The tethered control of the Sahara system allows the hydrophone to stop at precise locations for each interval. Time of arrival data is then used to calculate the average wall thickness over each interval. Since the wall thickness average intervals are defined by hydrophone location there are infinite interval possibilities limited only by the amount of time and resources available for the inspection.

Sahara wall thickness has the same limitations on survey as the leak detection system. Also like the leak detection, air pockets can significantly interfere with the wall thickness measurements as they affect the acoustic signal propagation. It is important to note that the wall thickness measurements resulting from this technique are only an average thickness over a range of pipes

Average wall thickness results need detailed pipe information and fluid parameters for calculations. Current testing procedure requires an access (i.e. hydrant, flange, or exposed pipe surface) a minimum of every 400 feet to generate reference acoustic signals.

Some factors affecting wall thickness accuracy include:

- Distance of a given section (the shorter, the more uncertain)
- Distance readings of the sections
- Accuracy of the pipeline and fluid parameters
- Unknown pipe features
- Rehabilitation, or large stationary air pockets

However, many pipeline related factors can be eliminated through a repeat inspection.

Before each Sahara Wall Thickness test adequate calibration and preparation is performed to ensure high quality. This includes:

- Calibration of Sahara sensor's sensitivity and distance reading
- Calibration of reference acoustic sensor for synchronization with Sahara
- Repeatability tests

A relative result is obtained based on all calculated results in every 30 foot interval. A nominal pipe wall thickness would be calculated from a group of intervals that shows similar wall thickness results (< 2% difference from the mean), and the result of other portions would show the wall thickness change ratio to this nominal value. This relative result is provided instead of calculated wall thickness to eliminate and minimize possible uncertainties introduced by composite pipe material and alterable fluid parameters.

## 3.2 Sahara Tests

### 3.2.1 Sahara Test Schedule

A total of five Sahara insertions were performed from July 13th to July 17th for all the different inspection technologies. The Sahara video inspection was performed first, on July 13th, to inspect the inside of the pipeline. This inspection identifies potential obstacles for other internal inspections as well as internal corrosion and air pockets. The Sahara video head was inserted into Pit 1 and traversed the line using the pipeline flow. After reaching Pit 3 the video head was then retracted and taken out of Pit 1.

Sahara Leak Detection was performed on July 14th, 15th, and 17th. Three full surveys of the pipeline were performed to test different arrangements of simulated leaks and perform a repeatability survey under varying conditions. Like the Sahara video head, the Sahara sensor head was inserted and retracted out of Pit 1. The leak detection survey was conducted during the deployment and retrieval of the sensor through the pipeline. On July 15th a thunderstorm required that flow in the pipeline be stopped due to reduced storm sewer capacity and the survey ended before completion.

Sahara Wall Thickness Testing was performed on July 15th and 16th in conjunction with Sahara Leak Detection. The Sahara sensor head was inserted into Pit 1 and secondary external sensors were installed at Pits A, C, E, and 3. Multiple test reference signals were generated at each of the pits to conduct the wall thickness measurements.

**Table 3.1 Insertion Details**

| Date | Insertion Point | End Point | Survey Length (ft) | Flow Direction | Description |
|---|---|---|---|---|---|
| July 13th | Pit 1 | Pit 3 | 2057 | East | Video |
| July 14th | Pit 1 | Pit 3 | 2050 | East | Leak Detection & Leak Simulations |
| July 15th | Pit 1 | After Pit F | 1797 | East | Leak Simulations |
| July 16th | Pit 1 | Before Pit 3 | 1984 | East | Wall Thickness |
| July 17th | Pit 1 | Pit 3 | 2050 | East | Repeat Leak Detection, Simulations & Wall Thickness |

## 3.3 Sahara Results

### 3.3.1 Sahara Video Survey Results

The Sahara Video inspection of Westport Rd. Transmission Main successfully identified several significant observations. Details of the observations are presented in Table 3.2, specifically the direction and distance the observation was found from the insertion point (Pit 1).

**Table 3.2 Observation Details**

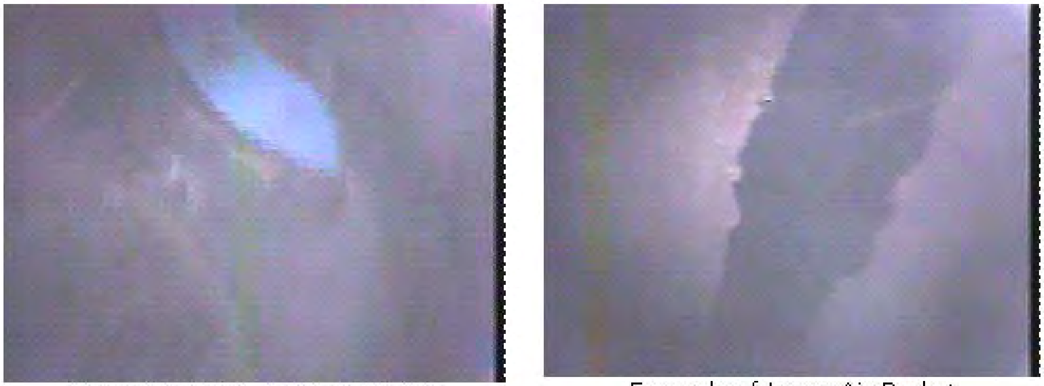
| # | Description | Estimated Distance from Pit 1 (ft) | Direction from Insertion | Potential Correlated Pipe Feature |
|---|---|---|---|---|
| 1 | Outlet | 154 | Downstream | |
| 2 | Outlet | 677 | Downstream | |
| 3 | Air pocket | 886 | Downstream | |
| 4 | Large air pocket | 1024 | Downstream | |
| 5 | Outlet | 1061 | Downstream | Pit 2 (1080 ft) |
| 6 | Large air pocket | 1237 | Downstream | |
| 7 | Outlet | 1552 | Downstream | Pit 5 (1580 ft) |
| 8 | Corrosion | 1565 | Downstream | |
| 9 | Outlet | 1628 | Downstream | |
| 10 | Large area of corrosion | 1637 | Downstream | |
| 11 | Outlet | 1755 | Downstream | Pit F (1750 ft) |
| 12 | Outlet | 1946 | Downstream | |

Many additional air pockets, ranging from small to large in size, were discovered during the video inspection. Both air pockets and wall corrosion could be clearly distinguished in the video inspection.

**Figure 3.5 Sahara Video Examples**

Close-Up of a Joint Gap at the Insertion

Example of an outlet



Extraction Point, 24x24x12" Tee

Example of Large Air Pocket

### 3.3.2 Sahara Leak Detection Results

The Sahara Leak Detection of Westport Rd. Transmission Main successfully identified 6 natural leaks and 14 simulated leaks. Details of the natural leaks are presented in Table 3.3, specifically the direction and distance the leak was found from the insertion point. The most accurate method to locate a leak is from the mark created above ground by the inspection team during the survey.

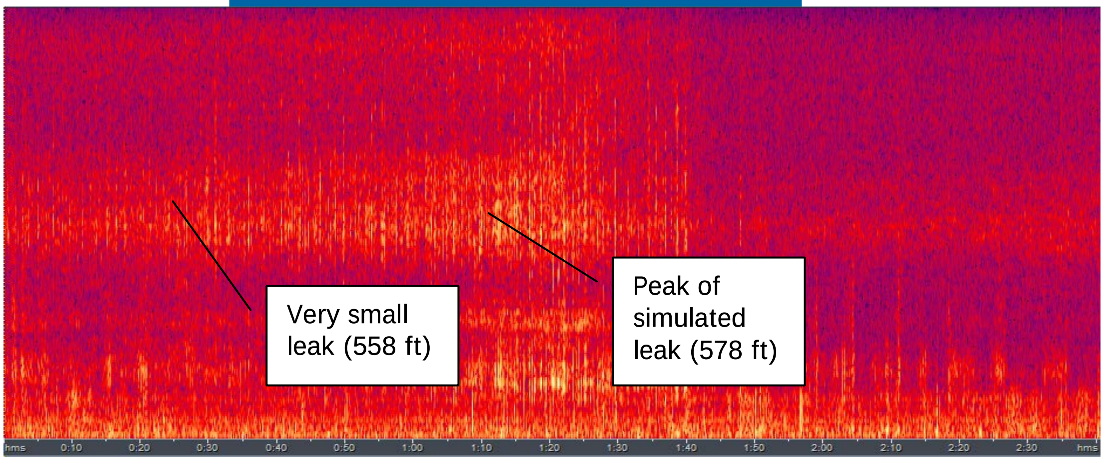
**Table 3.3 Natural Leak and Air Pocket Details**

| Leak # | Feature | ~Distance from Pit 1 (ft) | Direction from Insertion Point |
|---|---|---|---|
| 1 | Very Small Leak | 50 | Downstream |
| 2 | Very Small Leak | 194 | Downstream |
| 3 | Large Leak | 338 | Downstream |
| 4 | Very Small | 558 | Downstream |
| 5 | Small Leak | 638 | Downstream |
| - | Large Air Pocket | 900 | Downstream |
| 6 | Very Small Leak | 1696 | Downstream |
| 7 | Small Leak | 1906 | Downstream |

Simulated leaks were rearranged several times. Each simulated leak was a combination of one to three consecutive leaks, from orifices of different sizes, arranged one to two feet apart. When individual leaks are at close proximity, the leak signatures combine and do not necessarily differentiate. Details of the detected simulated leaks are presented in Table 3.4, specifically the arrangement number, direction, and location.

The following screen capture is from the simulated leak recording located at pit 4, from 541 ft to 607 ft. A small peak around 558ft shows a very small natural leak. Signatures of both leaks are combined and are difficult to report in real-time.

Figure 3.6 Close Proximity Leaks



Very small leak (558 ft)

Peak of simulated leak (578 ft)

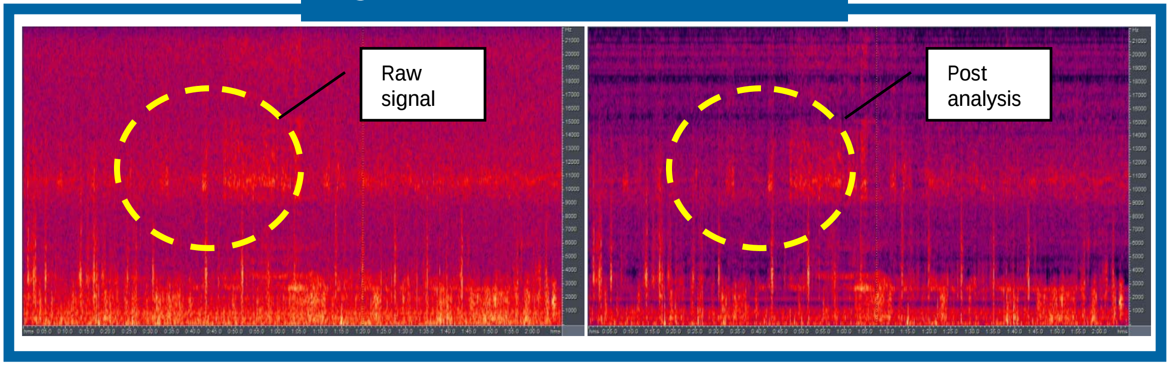
**Table 3.4 Simulated Leak Details**

| Arrangement # | Date | Leak Classification | Location |
|---|---|---|---|
| 1* | July 14th | Very small | Pit 4 |
| 1 | July 14th | Small | Pit 2 |
| 2 | July 14th | Large | Pit 5 |
| 2 | July 14th | Very small | Pit 2 |
| 2* | July 14th | Very small | Pit 4 |
| 3 | July 15th | Small | Pit 4 |
| 3 | July 15th | Small | Pit 2 |
| 3 | July 15th | Medium | Pit 5 |
| 4 | July 15th | Medium | Pit 5 |
| 4 | July 15th | Small | Pit 2 |
| 4* | July 15th | Very small | Pit 4 |
| 5 | July 17th | Small | Pit 4 |
| 6 | July 17th | Very small | Pit 4 |
| 7 | July 17th | Very small | Pit 4 |

*These leaks required post analysis. Leak signal could be masked by air pockets, water discharge, and/or electrical issues.

After recording signals from inspections, PPIC used post analysis to filter noise and improve leak detection. The signals were filtered and show that post analysis can make leak signals more distinguishable.

**Figure 3.7 Post Processed Leak**



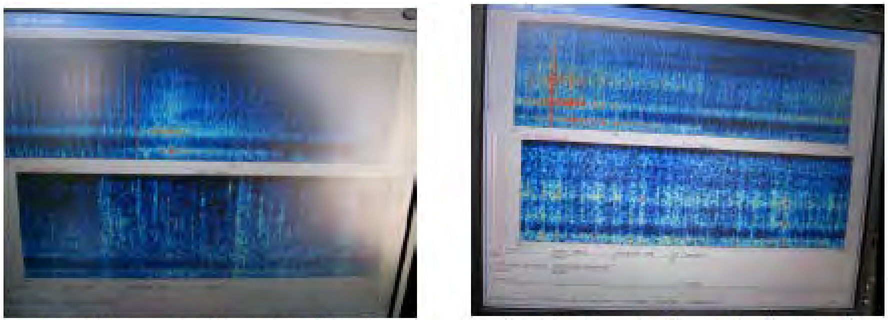
After initial inspection, the Sahara hydrophone was tested on-site and found to have technical problems. Subsequently, that particular hydrophone was replaced with an alternate hydrophone confirmed to pass quality control/assurance tests. Two of the very small leaks were re-simulated and were detected on-site using the new hydrophone. As a precaution, all Sahara hydrophones are tested onsite following standard QC/QA procedures prior to inspection.

Leak classification is mainly based on the distance away from a leak that the leak can be detected. In pipes of diameter 24" to 60", leak classification is believed to represent leak sizes shown in Table 3.5.

**Table 3.5 Leak Classification**

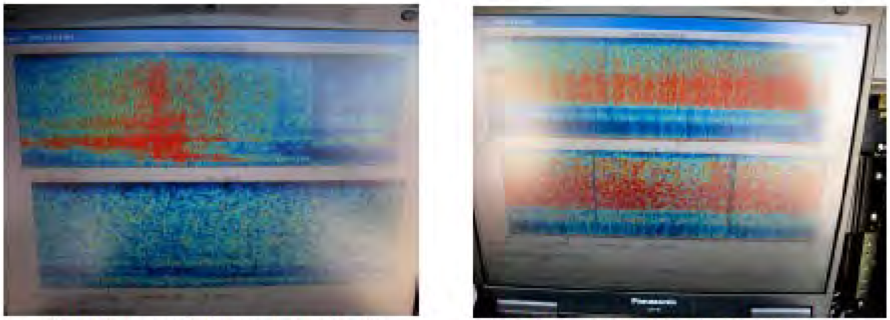
| Classification | Distance detected | Approx. Measured Size | | | |
|---|---|---|---|---|---|
| | | Min m3/hr | Max m3/hr | Median m3/hr | Median gpm |
| Very small | 0 – 2 m | 0 | 0.4 | 0.2 | 0.88 |
| Small | 2 – 5 m | 0.4 | 4 | 2 | 8.8 |
| Medium | 5 – 15 m | 4 | 17 | 10 | 44 |
| Large | 15 – 50 m | 17 | 29 | 23 | 101 |
| Very Large | 50+ m | 29 | 42 | 35 | 154 |

**Figure 3.8 Sahara Video Examples**



Signal Generated by a Small Leak

Signal Generated by a Medium Leak



Signal Generated by a Large Leak

Signal Generated by the Discharge Line

## 3.3.3 Sahara Wall Thickness Results

The Sahara Wall Thickness Assessment of Westport Rd. Transmission Main successfully identified specific areas of wall thickness loss. Details of the wall thickness loss are presented in Table 3.6, specifically the pipeline interval and average result over that interval.

| Table 3.6 Thickness Details | |
|---|---|
| **Distance from Pit 1 (ft)** | **Average Wall Thickness Loss Ratio (%)** |
| 0-17 | N/A |
| 17-33 | < 15% |
| 33-66 | Nominal |
| 66-98 | < 15% |
| 98-131 | Nominal |
| 131-164 | Nominal |
| 164-197 | Nominal |
| 197-230 | 15 - 30% |
| 230-295 | N/A |
| 295-328 | > 30% |
| 328-361 | > 30% |
| 361-394 | > 30% |
| 394-426 | Nominal |
| 426-459 | < 15% |
| 459-492 | 15 - 30% |
| 492-525 | < 15% |
| 525-558 | < 15% |
| 558-590 | < 15% |
| 590-623 | Nominal |
| 623-656 | < 15% |
| 656-689 | Nominal |
| 689-722 | 15 - 30% |
| 722-754 | 15 - 30% |
| 754-787 | Nominal |
| 787-1640 | N/A |
| 1640-1673 | Nominal |
| 1673-1706 | Nominal |
| 1706-1738 | < 15% |
| 1738-1771 | < 15% |
| 1771-1804 | < 15% |
| 1804-1837 | < 15% |
| 1837-1870 | Nominal |
| 1870-1902 | Nominal |
| 1902-1935 | 15 - 30% |
| 1935-2057 | N/A |

Pipeline intervals with an average wall thickness loss of less than 2% are listed as nominal. The average wall thickness loss ratio is in relation to the nominal mean value.

The section from 295 to 328 feet shows the highest wall thickness loss. Increased error margin in the section from 230 to 295 feet is due to the close proximity of internal and external sensors. Subsequently, a wall thickness loss ratio cannot be calculated for this interval. From 787 to 1640 feet a wall thickness ratio cannot be calculated due to presence of large air pockets and/or the proximity of sensors. The pipeline discharge masked acoustic activity after 1935 feet.

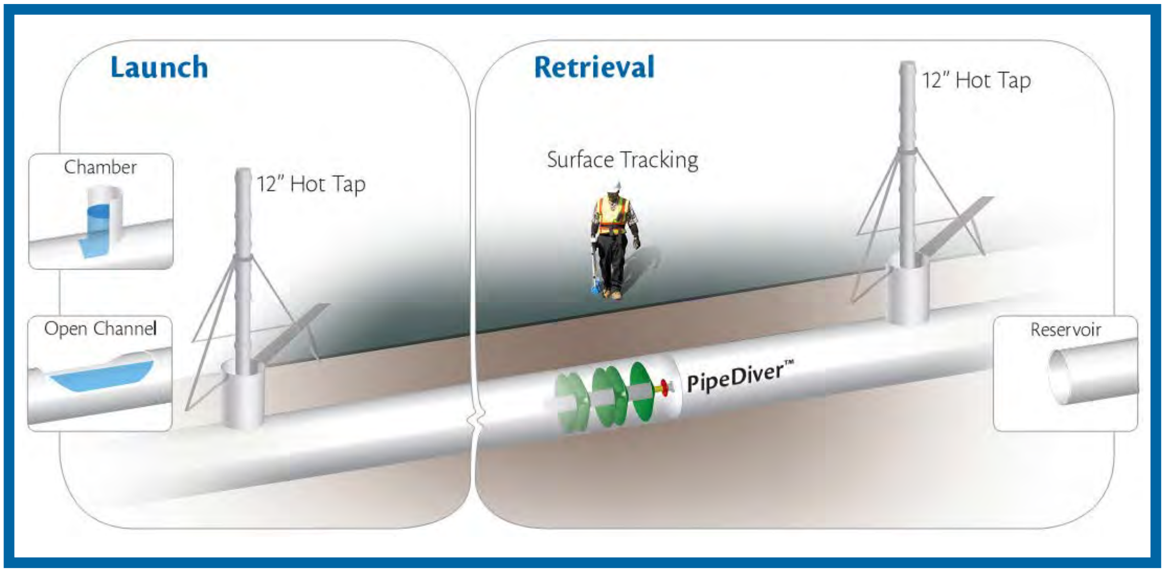
# 4. PIPEDIVER TECHNOLOGY

## 4.1 PipeDiver Background and Theory

### 4.1.1 PipeDiver Platform

The PipeDiver system has been specifically designed for use in pipelines that are live or can not be taken out of service due to lack of redundancy or operational constraints. PipeDiver provides accurate condition assessment of critical infrastructure, specifically detecting prestressing wire breaks in Prestressed Concrete Cylinder Pipe (PCCP). This solution offers significant cost savings as the pipeline remains in service eliminating the need for service shutdown and dewatering. The system has been proven effective for the inspection of live PCCP lines from the verification of its pilot inspection of 30 inch diameter pipe in Halifax in 2007.

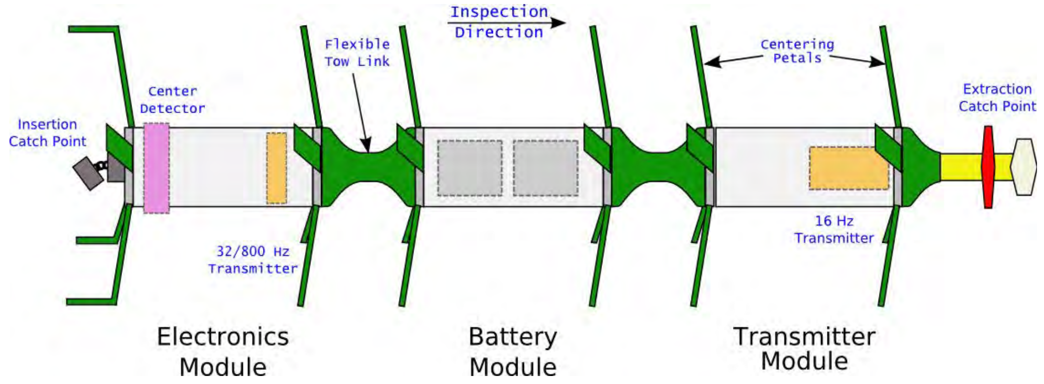
PipeDiver is a non-tethered, free swimming inspection platform for in-service water mains. The inspection vehicle allows inspection of pipelines from 24 inch in diameter and larger through two 12 inch diameter taps installed on the pipeline, one at each end of the inspection region. Alternatively, reservoirs or open channels can be used as insertion and extraction points.



For a standard launch the insertion tube containing the PipeDiver vehicle is attached to the 12 inch tap before being filled with water, pressure equalized, and opened to the pipeline. The internal insertion piston pushes the PipeDiver vehicle into the pipe and, once fully in the pipe, the vehicle is released and begins to travel with the flow. For a standard retrieval, once the PipeDiver vehicle reaches the extraction side, a robotic claw and net which blocks the entire pipe diameter grabs the front of the vehicle and secures it before pulling up out of the pipe and into the retrieval tube.

The PipeDiver vehicle travels at approximately 90% of the pipeline's flow rate, the neutrally buoyant inspection vehicle can run for up to 30 hours in a single insertion. Flexible fins are used to center the tool within the pipe and provide propulsion. Its flexible design ensures that PipeDiver can navigate through most butterfly valves and bends in the pipeline while travelling long distances.

**Figure 4.2 PipeDiver Retrieval Arm**



The PipeDiver inspection tool is inserted into a live main through a 12” tap directly on top of the main, then retrieved using a robotic arm inside a similar chamber at the end of each inspection run. The modular system includes an electronics module, battery module, and transmitter module for above ground tracking.

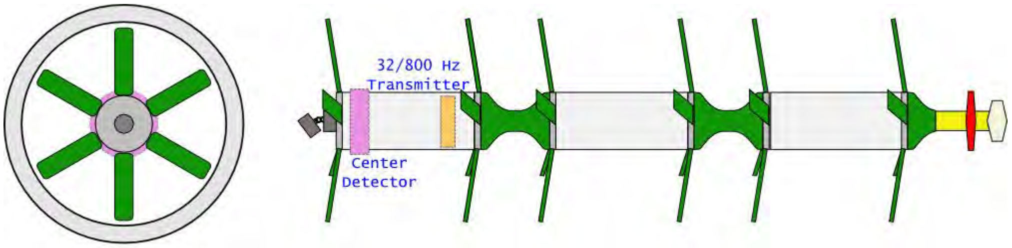
### 4.1.2 PipeDiver RFEC Testing Description

The Remote Field Eddy Current (RFEC) is a proven technique for non-destructive inspection of metallic pipelines. The PipeDiver is similarly a proven platform for insertion into live pipelines and inspection using the RFTC technique. While the RFTC and RFEC techniques are similar in nature there are several challenges involved in modifying the PipeDiver platform to support RFEC technology:

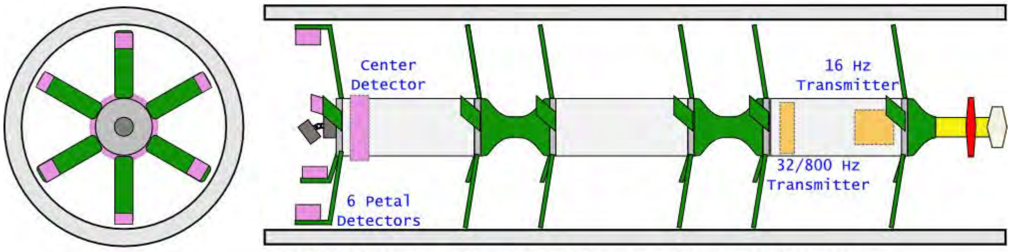
- Detectors have to be closer to the wall
- More detectors are required
- Signal levels are significantly lower than RFTC
- Exciter to detector axial separation is much larger

To modify the PipeDiver for a RFEC inspection the exciter coil was moved from the rear body near the center detector into the first body to achieve the minimum 1.5-2 pipe diameters required for the RFEC technique. Six additional detector coils were added to petals at the rear of the vehicle to provide increased sensitivity to wall thickness loss while still permitting the the vehicle to be inserted and extracted through a 12 inch diameter opening.

**Figure 4.4 PipeDiver Coil Locations**



Coil Setup for the RFTC Inspection Technique



Coil Setup for the RFEC Inspection Technique

The future challenges for PipeDiver RFEC development will be to increase the number of detectors close to the pipe wall, especially for larger diameter pipes, to increase the resolution and accuracy of the wall thickness measurements.

Common factors affecting accuracy for any RFEC system include the pipeline design and composition (i.e. metallic variations), inspection tool calibration, inspection tool riding quality, the type and position of the defect. Calibration details include running standard RFEC tests (with various coil separation/frequency setups) on pipes with a set of defects (size and shape) to achieve the best detection and sensitivity.

## 4.2 PipeDiver Testing

### 4.2.1 PipeDiver Inspections

PipeDiver RFEC Testing and trials were performed from July 21st to July 29th and four successful runs were completed. This was a pilot inspection using the RFEC technique in metallic pipe to obtain additional field data for analysis.

Table 4.1 shows the details of actual inspections, specifically the survey length and description of the inspection.

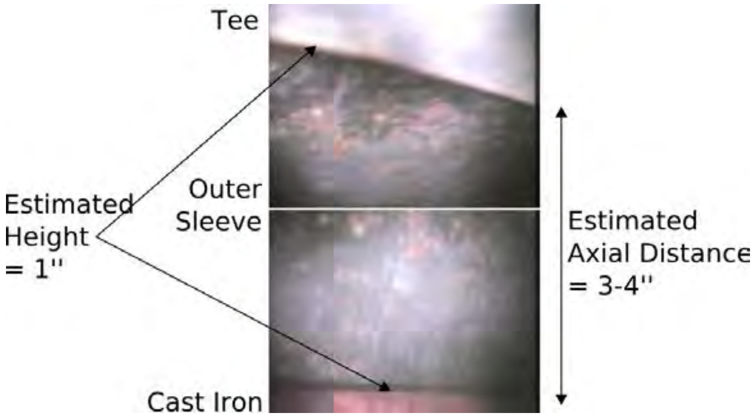
**Table 4.1 Insertion Details**

| Date | Insertion Point | End Point | Survey Length (ft) | Flow Direction and Speed | Description |
|---|---|---|---|---|---|
| July 23rd | Pit 1 | Pit 3 | 2057 | East, 1ft/sec | PipeDiver RFEC |
| July 24th | Pit 1 | Pit 3 | 2057 | East, 0.5 ft/sec | PipeDiver RFEC |
| July 27th | Pit 1 | Pit 3 | 2057 | East, 1ft/sec | PipeDiver RFEC |
| July 28th | Pit 1 | Pit 3 | 2057 | East, 1ft/sec | PipeDiver RFEC |

### 4.2.2 PipeDiver Insertion Issue

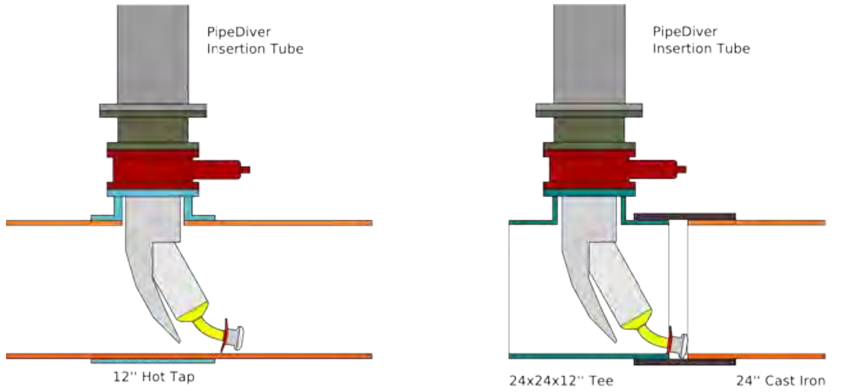
On July 21st, the first insertion attempt, the PipeDiver vehicle became stuck during the insertion process and that day's inspection had to be stopped and the vehicle retrieved from the pipe. An investigation of the issue with the help of Sahara video (Figure 4.5 and 4.6) led to the conclusion that the front of the PipeDiver has become stuck in a large, unfilled gap estimated to be 3 to 4 inches in width between joints just downstream of the insertion point.

**Figure 4.5 Sahara Video of the Joint Gap**



An alternate insertion process was designed and implemented and the following four insertions were successful.

**Figure 4.6 PipeDiver Insertion Schematic**



Original PipeDiver Design
Using Standard Hot Tap

Westport Rd. 24" Cast Iron Pipeline
Using a 24x24x12" Tee

PipeDiver is designed for live inspections using standard accesses including 12 inch diameter hot taps, tees with minimum joint gaps, or similar features. For certain accesses such as tees with large unfilled joint gaps or accesses with unknown internal conditions Sahara Video is recommended to identify the exact layout of the insertion point. The insertion design and process can then be modified for a successful insertion if required.

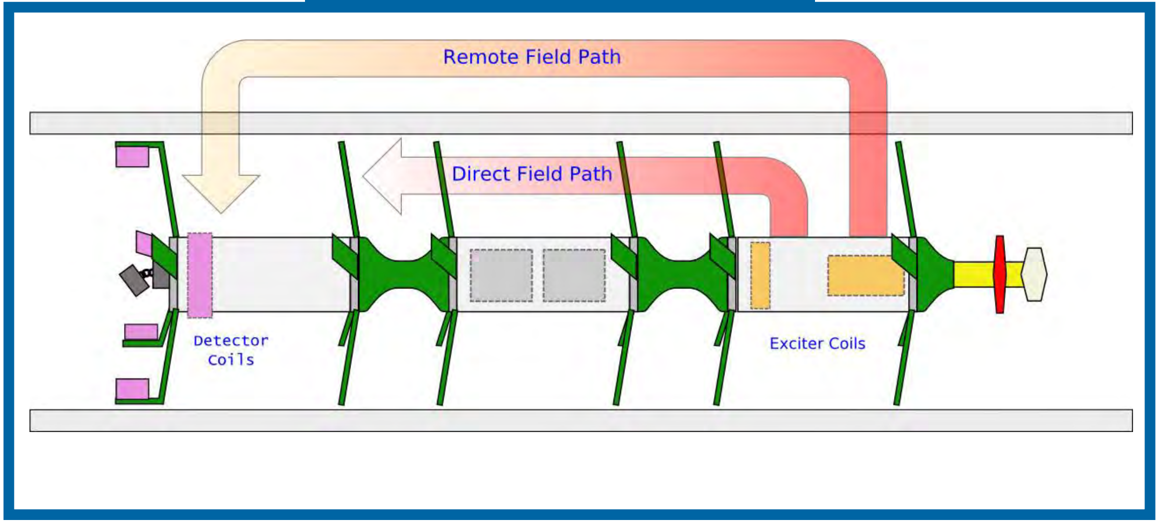
## 4.3 PipeDiver Results

### 4.3.1 PipeDiver RFEC Result Description

PipeDiver RFEC Testing was conducted as a pilot project to obtain field data for analysis.  Data was analyzed and characterized based on basic pattern recognition from simple models of wall thickness variations.

Remote Field Eddy Current works on the basic theory that when a time harmonic magnetic field is generated inside a metallic pipe it has two paths from the exciter to detector coils (see Figure 4.7).

**Figure 4.7 RFEC Signal Paths**



The direct path remains inside the pipe and couples the coils directly while the remote path remains outside of the pipe as long as possible. When the exciter-detector coil separation exceeds 1.5 pipe diameters the signal from the remote field significantly dominates the total signal received at the detector. Since the remote field path has passed twice through the pipe wall any variation in magnetic wall properties including wall thickness, conductivity, and magnetic permeability will result in a change in the detector signal.

### 4.3.2 PipeDiver RFEC Results Overview

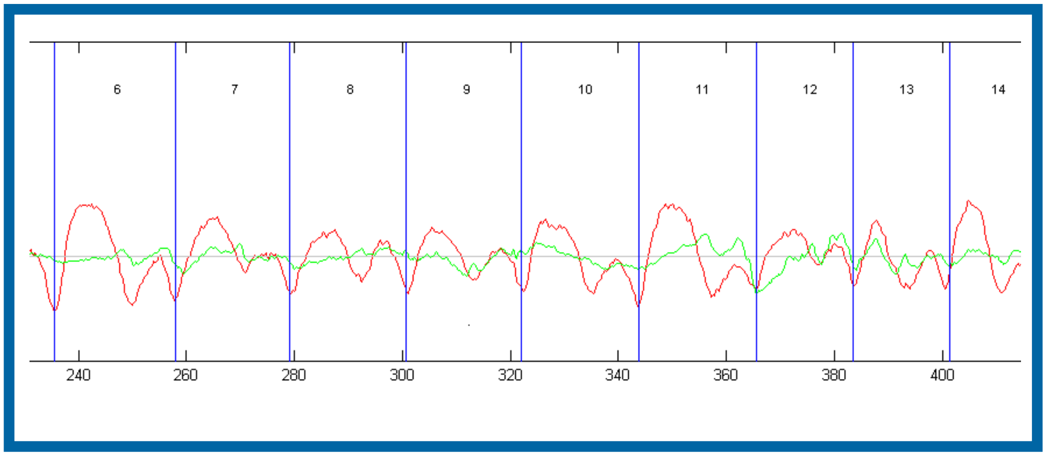
Table 4.2 lists the location of pipe sections PipeDiver data characterized as anomalous and their distance from Pit 1.

| Table 4.2 PipeDiver Anomalous Pipes | |
|---|---|
| Distance from Pit 1 (ft) | |
| **Start** | **End** |
| 216 | 228 |
| 264 | 276 |
| 276 | 288 |
| 324 | 336 |
| 360 | 372 |
| 384 | 396 |
| 444 | 456 |
| 504 | 516 |
| 516 | 528 |
| 576 | 588 |
| 612 | 624 |
| 864 | 876 |
| 936 | 948 |
| 948 | 960 |
| 1044 | 1056 |
| 1056 | 1068 |
| 1176 | 1188 |
| 1212 | 1224 |
| 1284 | 1296 |
| 1308 | 1320 |
| 1332 | 1344 |
| 1356 | 1368 |
| 1368 | 1380 |
| 1416 | 1428 |
| 1452 | 1464 |
| 1512 | 1524 |
| 1584 | 1596 |
| 1608 | 1620 |
| 1620 | 1632 |
| 1644 | 1656 |
| 1656 | 1668 |
| 1704 | 1716 |
| 1740 | 1752 |
| 1752 | 1764 |
| 1788 | 1800 |
| 1812 | 1824 |
| 1860 | 1872 |
| 1872 | 1884 |
| 1908 | 1920 |
| 1956 | 1968 |
| 1992 | 2004 |

### 4.3.3 PipeDiver RFEC Pipe Signals

Figure 4.8 below shows the center detector signal amplitude (red) and phase (green) from the July 23rd inspection of a section of pipeline which is classified as containing normal pipes.

**Figure 4.8 PipeDiver RFEC Nominal Pipes**



Each joint is composed of a double signal due to the remote field effect. One signal is from the exciter passing the joint and one from the detector passing. The first signal in a joint is generally higher and longer due to the relative lengths of the pipe and axial exciter-detector coil separation, 12 and 5.5 ft respectively (Figure 4.9).

**Figure 4.9 PipeDiver RFEC Joint Detection**

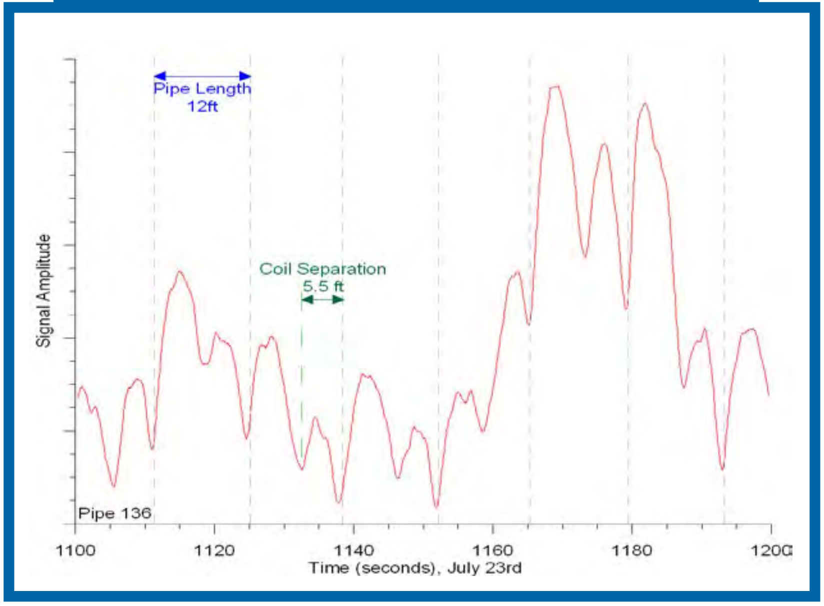
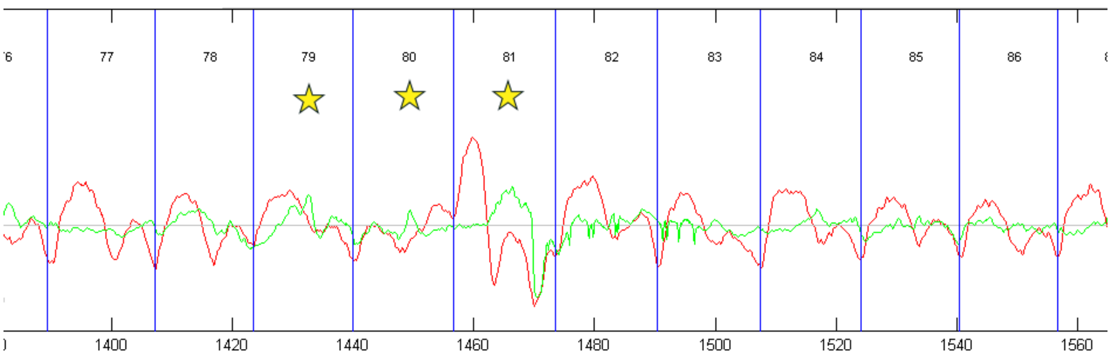


Figure 4.10 below shows an example of several pipes classified as anomalous from their RFEC signal. The second half of pipe 79 and the first half of pipe 80 show an anomalous signal which could be due to a wall thickness loss from pipe 80. The entire signal in pipe 81 differs largely from the nominal pipe signal and could be due to wall thickness loss or from an unidentified pipe feature.

**Figure 4.10 PipeDiver RFEC Anomalous Pipes**



The PipeDiver configuration used on the July 23rd and 28th inspections were almost identical which allows a direct comparison of the signals. Figure 4.11 below shows a comparison for a section of four pipes from the center detector. One of the objectives of this inspection was to verify the validity of the PipeDiver RFEC technology by performing such repeatability tests. The results from the multiple PipeDiver scans show good repeatability.

A known feature from the pipeline that is readily seen in the PipeDiver RFEC data is the hydrant outlet that is located near Pit F (Figure 4.12). While the signal is relatively small as compared to the joint signal it can be distinguished by having a double signal occurring the exact distance as the PipeDiver's detector-exciter coil separation distance.

**Figure 4.11 RFEC Repeatability**

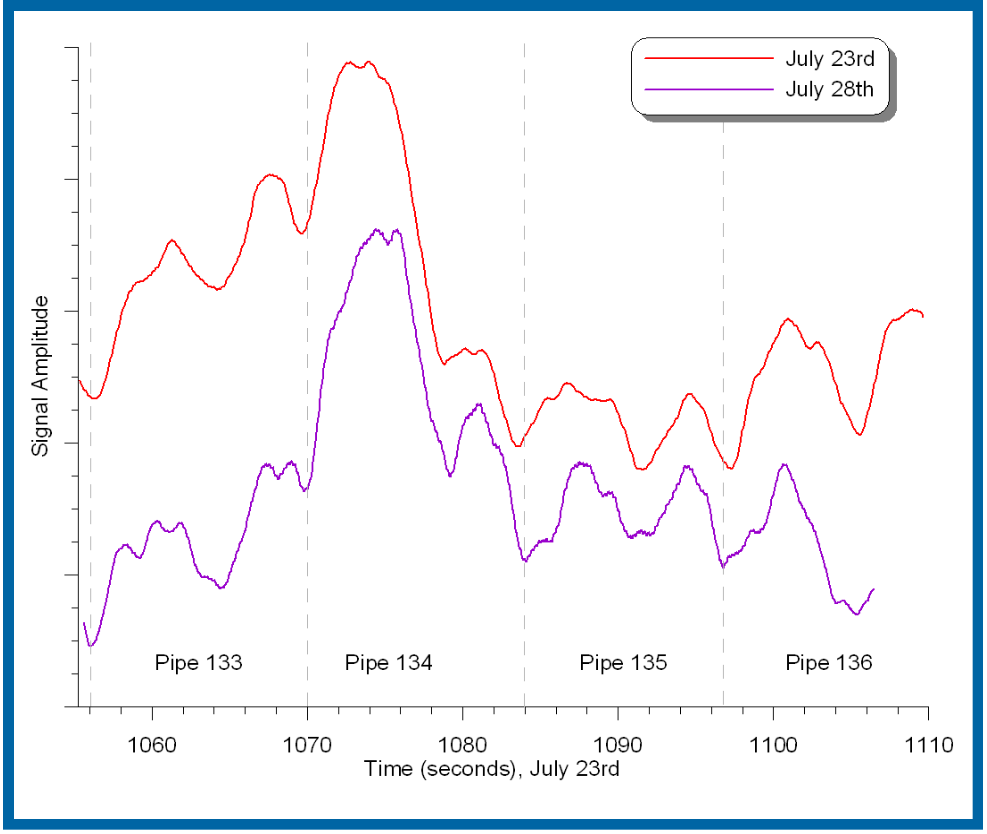
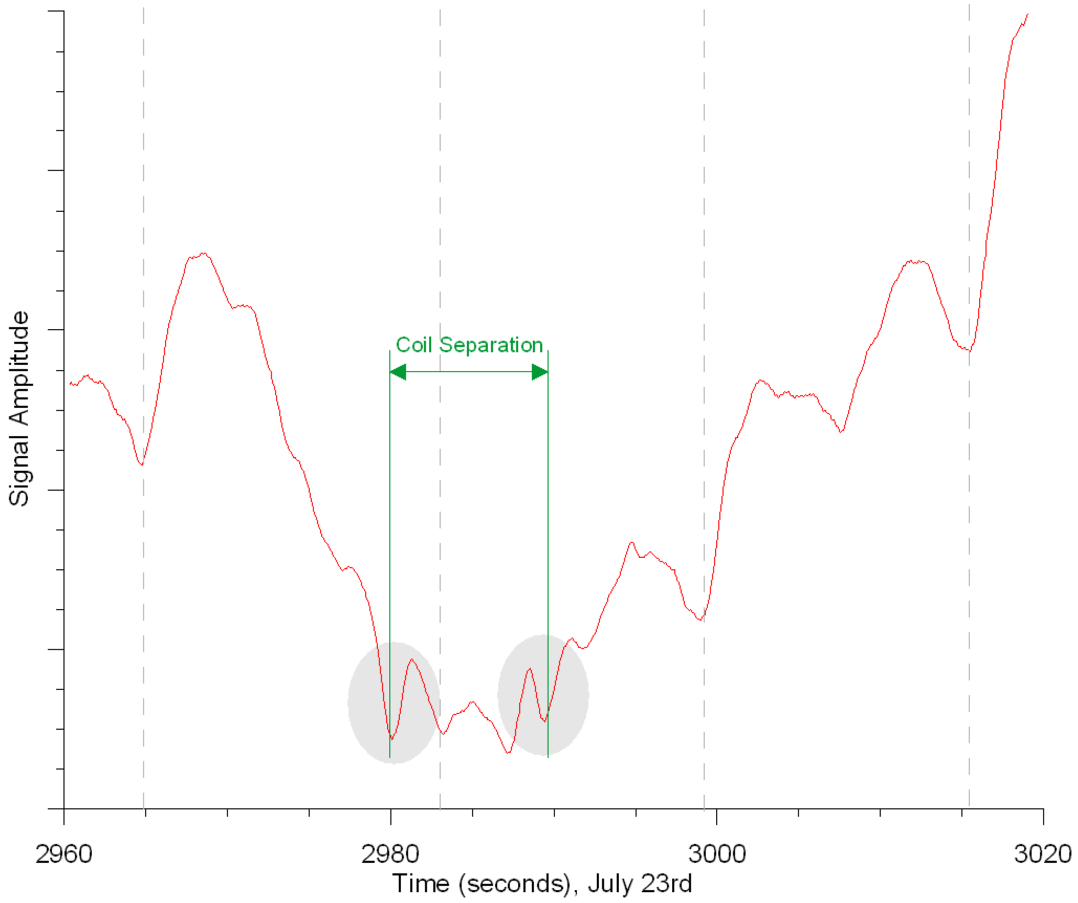


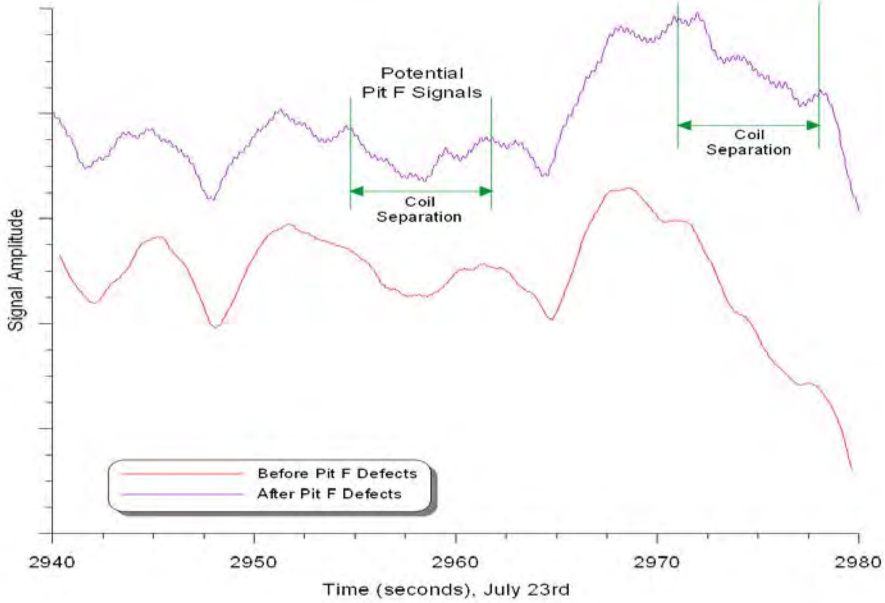
Figure 4.12 PipeDiver RFEC Hydrant Signal



Four new defects were machined into Pit F on July 28th (Figure 4.13). By comparing the RFEC signals from the data before and after the defects were created we have the best possible chance of seeing this relatively small amount of wall thickness loss in the data (Figure 4.14).

**Figure 4.13 New Pit F Defects**

**Figure 4.14 Comparing RFEC Data Before and After Defects**



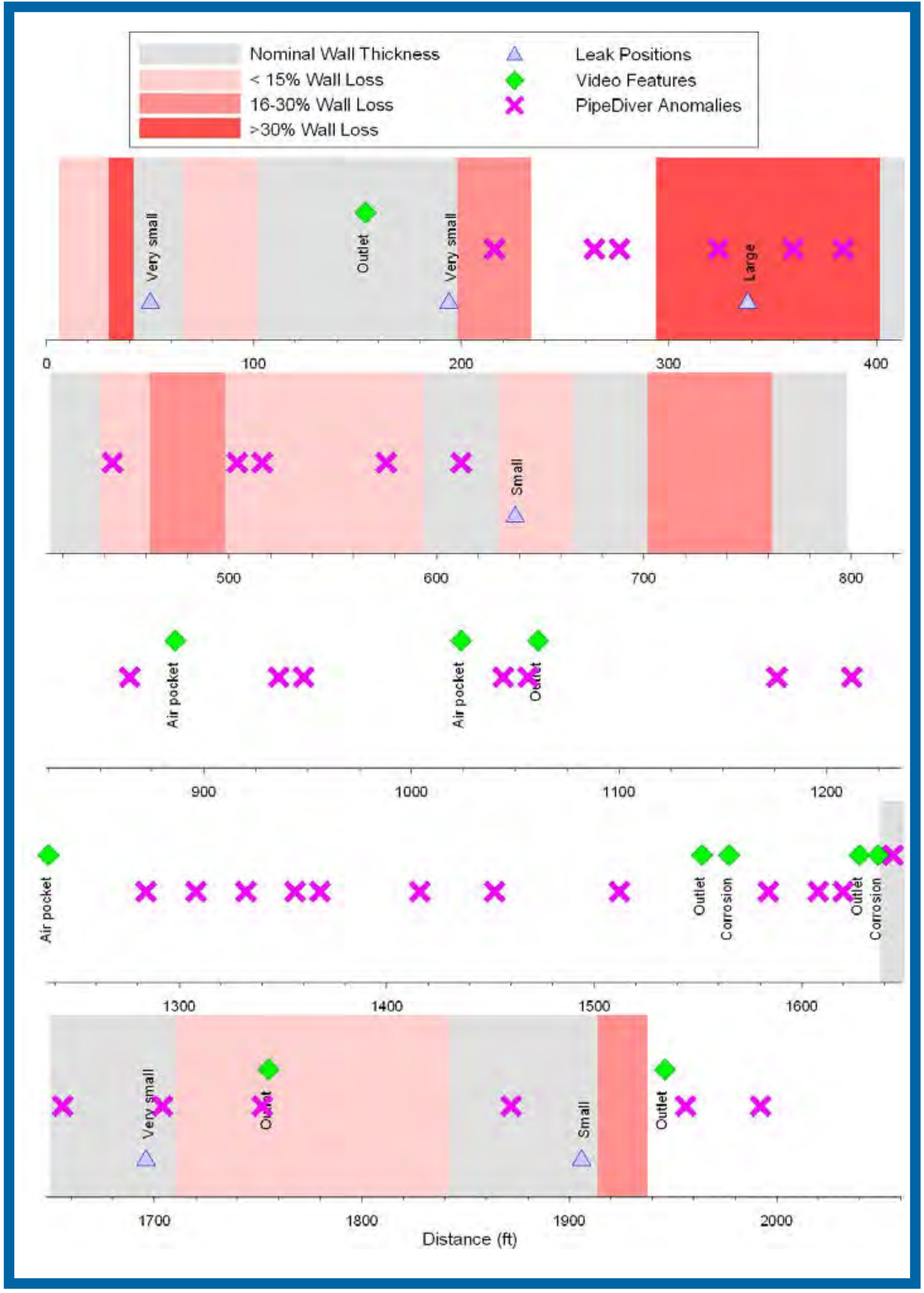
The PipeDiver RFEC results show good repeatability between multiple scans using the same configuration which validate it as a non-destructive inspection technique. The RFEC data clearly shows joint signals, known features and anomalous signals which may be potentially due to wall thickness loss. Further verification and calibration is needed to confirm the nature of these anomalous signals.

## 5. SUMMARY

### 5.1 Combined Test Results

The following figure 5.1 combines all results including Sahara Leak Detection, Sahara Video, Sahara Wall Thickness, and PipeDiver RFEC, showing their relative locations along the pipeline.

**Figure 5.1 Combined Results**



The combined results make it easier to identify potential areas of interest within the pipe. For example, the section between 300 to 400 ft contains a large leak, several PipeDiver RFEC anomalies and has a high average wall thickness loss and is one of the areas recommended for further verification and calibration. Similarly, the area between 1560 to 1640 ft contains several identified corrosion spots and PipeDiver RFEC anomalies.

## 5.2 Inspection Conclusions

PPIC's evaluation of the Westport Rd. Transmission Main between Pit 1 and Pit 3 (2057 foot section) provided an overall condition assessment of the metallic pipeline.

The Sahara platform was used to provide three critical non-destructive condition assessment services, including:

- Internal video inspection
- Leak detection
- Sahara and PipeDiver wall thickness assessment

All Sahara services were successfully inserted using a 2 inch tap in live conditions not requiring the line to be shut down. The tethered system allowed the sensor to be stopped at precise locations which enabled operators to make accurate and repeatable identifications regarding pipeline condition discoveries.

Sahara Leak Detection detected six unidentified leaks and one air pocket, recorded and marked their above ground position, and estimated the leak size all in real time. Several simulated leaks were also detected in real time, and post analysis was able to identify all leaks that had been masked by external noise factors such as the pipeline discharge.

Sahara Video's tethered CCTV inspection was also successfully deployed using a 2 inch tap. Real time analysis of the video provided insight into the internal condition of the pipeline and clearly distinguished two areas of corrosion. Air pockets and outlets were also clearly identifiable from the real time inspection. The second purpose of a video inspection, to discover possible obstacles for a PipeDiver inspection, showed that PipeDiver could be used with no risk from unidentified obstacles. Video recordings were used for post analysis and helped identify a previously unknown risk: a joint gap just downstream of the insertion point. These video results can now be used to improve and change aspects of the PipeDiver system.

Sahara Wall Thickness was performed in conjunction with leak detection thus minimizing extra resources and time. Analysis of the results uncovered specific intervals of the pipeline showing higher wall thickness loss than others. By utilizing the tethered Sahara system and being able to stop the hydrophone at precise locations, consistent and multiple pipe intervals could be set to calculate average wall thickness readings.

The PipeDiver platform is poised to becoming the industry standard for in-service pipeline inspections. The technology can be modified for different services and eliminates the need to take pipelines out of service during inspections. PipeDiver was successfully inserted and retrieved via two 12 inch Tees installed into the live main. Results obtained form the Westport Rd. Transmission main inspection have identified anomalous signals and processes that will allow PPIC to further improve the PipeDiver system, specifically RFEC Testing.

### 5.3 Advantages and Limitations

The significant advantage to the overall Sahara inspection technologies is that its tethered cable design brings the sensor as close as possible to the leak and allows unlimited control of the sensor position. For Sahara Leak Detection this means that the farthest the hydrophone sensor will be from a leak is the pipe diameter, or more realistically the pipe radius, which permits very small leaks to be detected. Leaks are detected in real time and immediately accurately located and marked above ground.

The primary limitation of the Sahara system is the same as its main advantage: its tethered cable design. The inspection length possible from an insertion point is limited by the amount of available cable as well as the amount of flow in the pipe line and how far this flow can carry the hydrophone and cable through the pipe before friction stops it.

Sahara Video permits a real time video inspection of a live pipeline and only requires a 2 inch access although it has the same cable and inspection limitation and the video quality is reduced in larger diameter pipes.

The Sahara Wall Thickness technique allows flexible distance and better interval resolution from the cable control but can only indicate the average wall thickness in a section and not specific defects.

PipeDiver is a proven platform designed for live inspection of PCCP using the RFTC technology but has been adapted to use the RFEC technique to provide wall thickness loss in metallic pipelines. The detection sensitivity is limited by the number of sensor channels but since the significant challenge of non-disruptive inspection has been overcome future development can focus on increasing the number of available detectors.

The Sahara and PipeDiver techniques are complementary technologies that offer a spectrum of solutions to utilities. By detecting very small leaks and accurately pinpointing the leak position, Sahara leak can provide pinhole corrosion in pipe wall and joint problems, which are a good indication of pipe condition. For wall thickness issues, including graphite, wall thinning, but not yet leaking, Sahara Wall Thickness can provide average sectional wall thickness info during the same time with Sahara leak and PipeDiver RFEC will be able to provide more detailed information. Also, Sahara Video provides internal line condition and visual corrosion information. All are live inspections that take place while the pipeline remains in service.

## 5.4 Future Developments

Sahara Leak Detection is a mature technology used successfully for many years and future development of the technique will focus on making it even easier to use. The main challenge with Sahara Video is to improve its video and lighting quality in larger diameter pipes and to possibly combine the video and leak techniques into a single sensor head which would reduce the amount of insertions required and make the overall inspection more efficient. The Sahara Wall Thickness technique will continue to fine tune its field and analysis procedure in addition to more verification and calibration.

PipeDiver is a proven platform for entering a pipe through a standard access in live conditions and for inspection of PCCP. Using the data and experience obtained from this first PipeDiver RFEC inspection pilot PPIC will be able to further improve the PipeDiver system for metallic pipeline inspections. Technical components will be reviewed for possible advancements including improved detectors and detector placement. As well, the analysis process will be reviewed for new analysis techniques and improved software. Specifications and implementations of standard accesses will be reviewed to prevent future insertion and retrieval issues. Results need to be compared to actual pipe calibration and verification from the Westport Rd. Transmission Main in order to review and improve the current analysis techniques.

## 6. PHOTOGRAPHS

Sahara insertion site with valve and tap in Pit 1.

Sahara control center (truck) and Sahara insertion setup at Pit 1.

Valve creating a simulated leak in Pit 4.

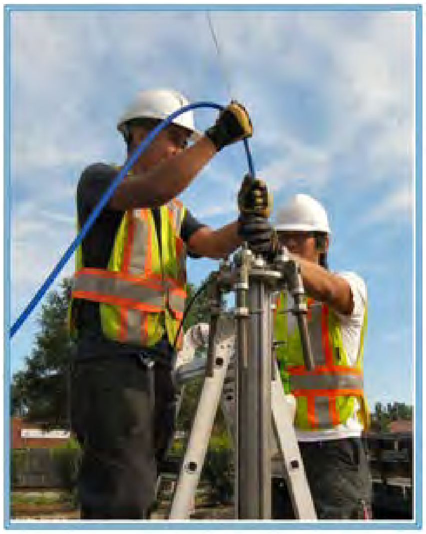
Pits were constantly flooded due to ground water and rain storms.

PipeSpy locating a simulated leak at Pit 4

Orifice used to create simulated leaks

The Sahara Video sensor head and drogue.

Technicians inserting the Sahara hydrophone into the pipe in live conditions.



The Sahara insertion tube setup in Pit 1.

Acoustic unit recording reference sound signals at the insertion point.

Accelerometer acoustic sensor attached to the Sahara insertion tube.

Carrying the PipeDiver tool ready to be installed into the insertion tube.

Preparing the PipeDiver insertion and retrieval tubes.

PipeDiver insertion tube setup at the launch site.

Attaching the PipeDiver extraction tube on the gate valve.

**Setting up the PipeDiver extraction tube.**

Technicians locating the PipeDiver vehicle from above ground.

APPENDIX C

# SmartBall® Pipe Wall Assessment Survey

## 24” Cast Iron Pipeline with Mortar Lining

## Louisville, Kentucky

Prepared For:
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

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Prepared By Vinh Nguyen
Pure Technologies Ltd
705 – 11th Ave. SW
Calgary, Alberta
Canada
T2R-0E3

January 5, 2009

# 1.0 Executive Summary

In partnership with the Environmental Protection Agency and Battelle Memorial Institute, Pure Technologies was given the opportunity to conduct leak detection and pipe wall assessment on a waterline in Louisville Kentucky. The pipeline assessed was a 24 inch steel water pipeline with mortar lining. The inspection was done using Pure Technologies' proprietary leak detection technology SmartBall and Pipe Wall Assessment technology.

The SmartBall was deployed to assess the pipe wall condition of 2057 ft of 24 inch cast iron pipeline in Louisville Kentucky on Thursday August 6th and Friday August 7th, 2009. Each combination of pipe wall assessment and leak detection survey took approximately one hour to perform. The SmartBall was able to detect a total of 15 non-simulated leaks as presented in the SmartBall Leak Detection Survey report. This report details the results from the pipe wall assessment portion of the inspection.

# 2.0 Summary of Technology

Maintaining and monitoring of municipal water and waste water pipelines is extremely important because leakage of water pipeline can lead to financial loss and loss of service. More importantly, leakage in waste water pipelines poses a threat to the environment and the general population. As such, utilities owner require a method of assessing the pipe wall thickness of the pipelines to efficiently manage and maintain their infrastructure.

The preferred method of assessing the condition of the pipe wall thickness would be a method that does not involve de-watering the pipelines or does not require the excavation of the pipes. Therefore, a non-destructive method of assessing the pipeline is most preferred as it is the most cost effective and it does not disrupt services.

Pure Technologies' pipe wall assessment (PWA) technology is a non-disruptive technology that uses low frequency pulses to evaluate the hoop stiffness of the pipe. The pipe wall condition is assessed by effectively measuring the propagation velocity of the transmitted pulse. By calculating the velocity of the wave as it propagates in the pipe, one can essentially determine the hoop stress of the pipe and in effect the pipe wall condition. Pure's PWA technology utilizes the SmartBall™ acoustic sensor and long range capabilities to assess the pipe wall condition and detect leaks simultaneously.

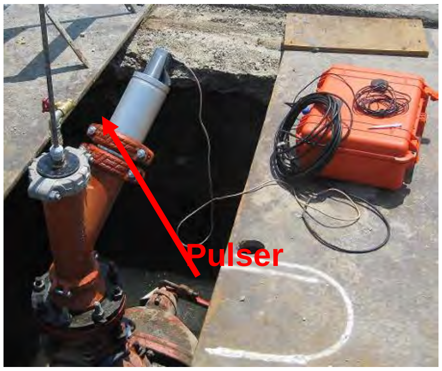


**Figure 2.1: Insertion stack with pulser**

The low frequency pulses are generated by pulsers mounted onto the SmartBall™ insertion stack, extraction stack, and intermediate locations along the pipeline. The pulser can also be mounted to typical fittings found on pipes, such as valves, and can also be strapped onto the pipe itself. The number of pulsers used is dependent on the length of the inspection. The Louisville Kentucky inspection required the use of three pulsers. The propagation velocity of the pulse is measured based on the arrival time of each pulse as compared to the previous pulse. The pipe wall stiffness in the interval traversed by the Smartball™ between the pulses is calculated based on the propagation velocity of the pulse. As the pipe wall stiffness decreases and increases, the propagating velocity of a low frequency acoustic wave moving through the water also decreases or increases respectively.

The low frequency pulse generated by the pulser can be obscured by loud noise sources nearby and propagation of the wave generated can be diminished by bends and elbows in the pipe. In order to compensate for the attenuation, three pulsers were used to ensure that the SmartBall would detect at least one pulse at any given time. Furthermore, the spatial resolution of the SmartBall™ PWA technology is also dependent on the velocity of the SmartBall™. The spatial resolution of the SmartBall™ PWA tool for the subject run was approximately 1 data point every 2 ft. As stated, the pipe wall stiffness was assessed at 2 ft. intervals and is unlikely to detect individual pits. However, it is an effective tool to highlight areas where a cluster of pits compromises hoop stiffness, or where there is a general deterioration of the pipe wall.

# 3.0 Pipeline Summary

| | |
|---|---|
| Project Date | August 6th and 7th 2009 |
| Service | SmartBall/Pipe Wall Assessment |
| Material | Cast Iron with Mortar Linings |
| Diameter | 24 inch |
| Pressure | 50 psi |
| Length | 2057 ft |
| Flow | 1.0 ft/s |

**Table 3.1: Summary of Inspection Details**

The approximate layout of the 24 inch cast iron water pipeline inspected started at the intersection of Chenoweth Lane and Westport Road, to the intersection of Ridgeway Avenue and Westport Road in Louisville, Kentucky. The approximate line location is displayed on the aerial photograph below in Figure 3.1.

Figure 3.1: General layout of the pipeline inspected.

As shown in Figure 3.1, the inspection required the use of three different pulsers positioned at the same locations as the surface sensors. Multiple pulsers were used to ensure that the SmartBall™ will always pick up the signals at any given time along the pipeline. Similar to the SmartBall™ and the SmartBall™ Receiver (SBR), the pulsers are synchronized. Furthermore, the use of multiple pulsers will compensate for the attenuation of the pulses by bends and elevation changes.

# 4.0 Tracking the Position of the SmartBall™

Knowing the position of the SmartBall™ within the pipeline is critical to accurately assess the pipe wall conditions. The methodology used to track the SmartBall™ involves obtaining a velocity profile using data obtained from the accelerometers and magnetometers on board the SmartBall™. Absolute position reference points obtained from the SmartBall™ Receiver (SBR) are applied to time stamped data. The three sensors used were able to track the SmartBall™ throughout the whole inspection without any blind spots. The result of the rotation profile and SBR tracking is a position versus time relationship for the entire inspection. The exact location of where each SBR was placed along the pipeline during the run is detailed in Appendix A.

An example of the data collected during the first of five inspections is shown below. Figure 4.1 shows the position data for the run. The position of the SmartBall™ indicated by the red line was fixed by fitting the position profile to known locations along the pipeline. The slope of the red line indicates the instantaneous velocity of the tool. The velocity of the SmartBall™ as it travelled through the pipeline for the first run is shown in Figure 4.2. Figure 4.3 displays the position of the ball as it was tracked in real time on site by the SBRs.

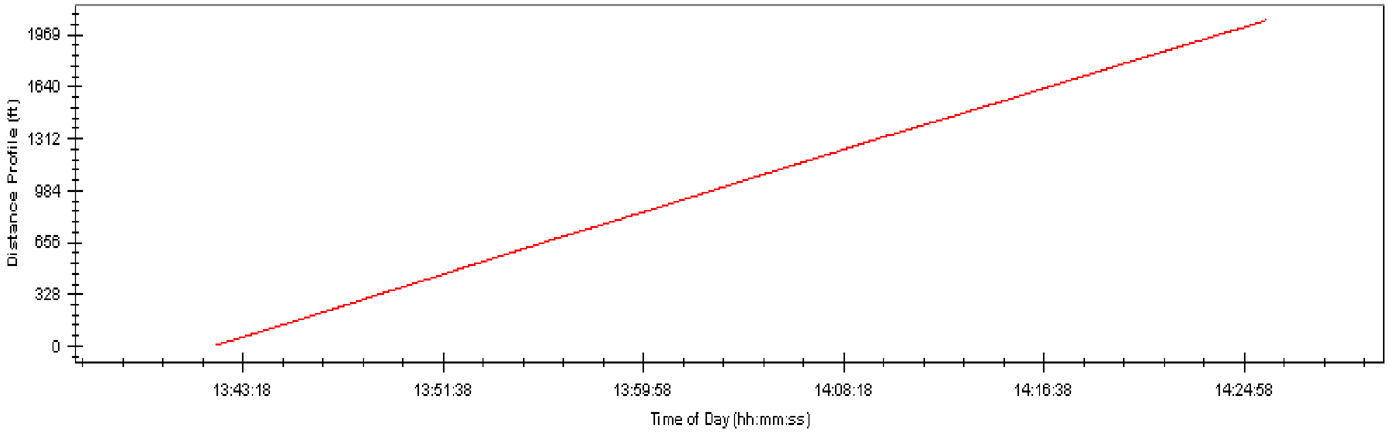


**Figure 4.1: SmartBall™ Position vs. Time for Run 1 (August 6th)**

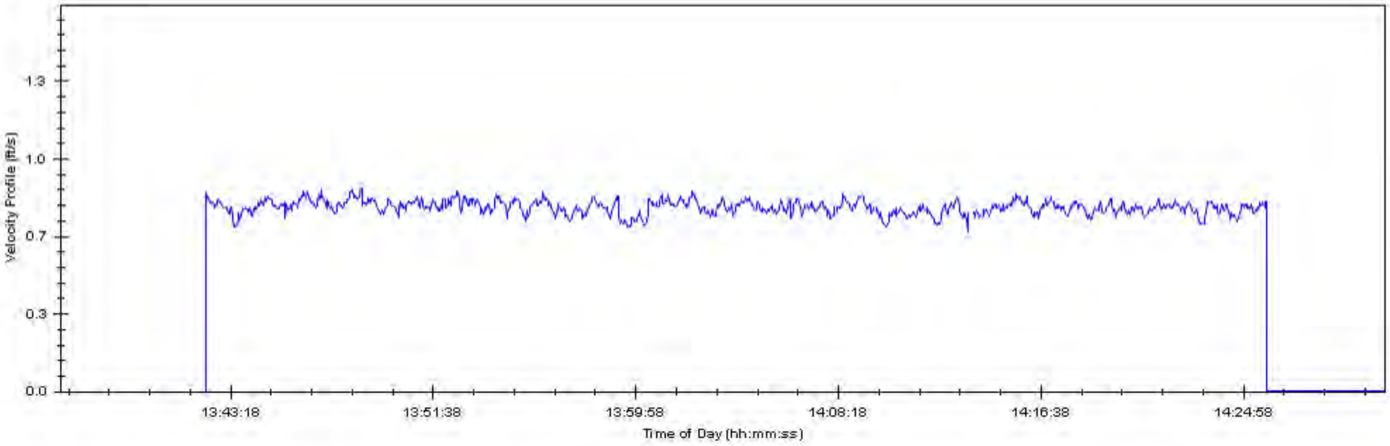


**Figure 4.2: Velocity Profile vs. Time of Day for Run 1 (August 6th)**

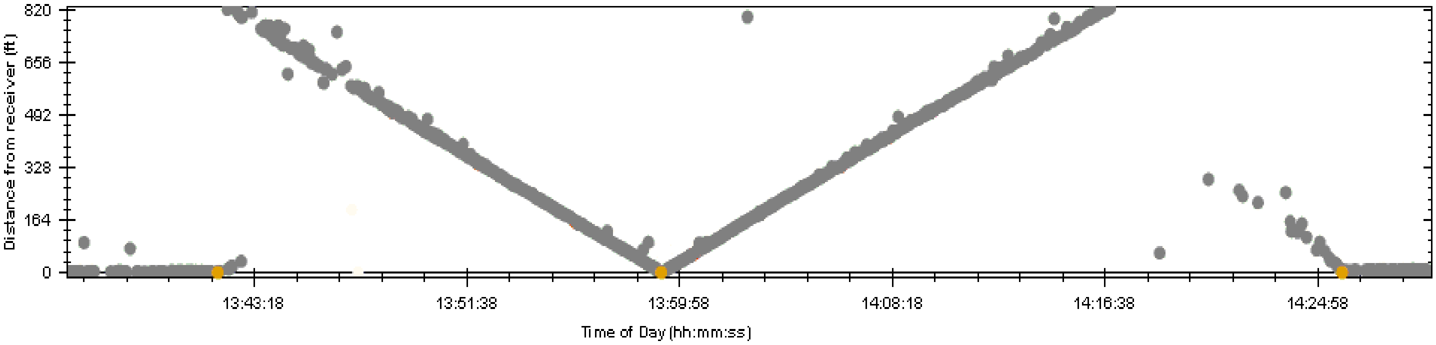


**Figure 4.3: SBR Tracking Point vs. Time of Day for Run 1 (August 6th)**

The SmartBall position profile, velocity profile and SBR tracking point data are shown above.

# 5.0 Results

Upon retrieval of the tool, the acoustic data recorded by the SmartBall™ PWA tool was analyzed and cross-referenced with the position data from the SBR to determine the location of the SmartBall™ during the inspection. The location accuracy of the anomalies is dependant on the accuracy of the pipe distance and lay information provided to Pure.

The signals transmitted from the pulser at the extraction site were obscured by the large amount of noise generated by the pressure control apparatus at the discharge line just past the extraction site. However, the signals from the first and second pulsers were detectable and those results are summarized below.

The graphs below show the condition of the pipe as detected by the SmartBall™ with respect to the position of the SmartBall™ along the pipeline. Since the pipe wall thickness affects the velocity of the signal as it propagates through a water filled pipe, it is therefore concluded that there is some evidence of pipe wall weakness at highlighted areas.

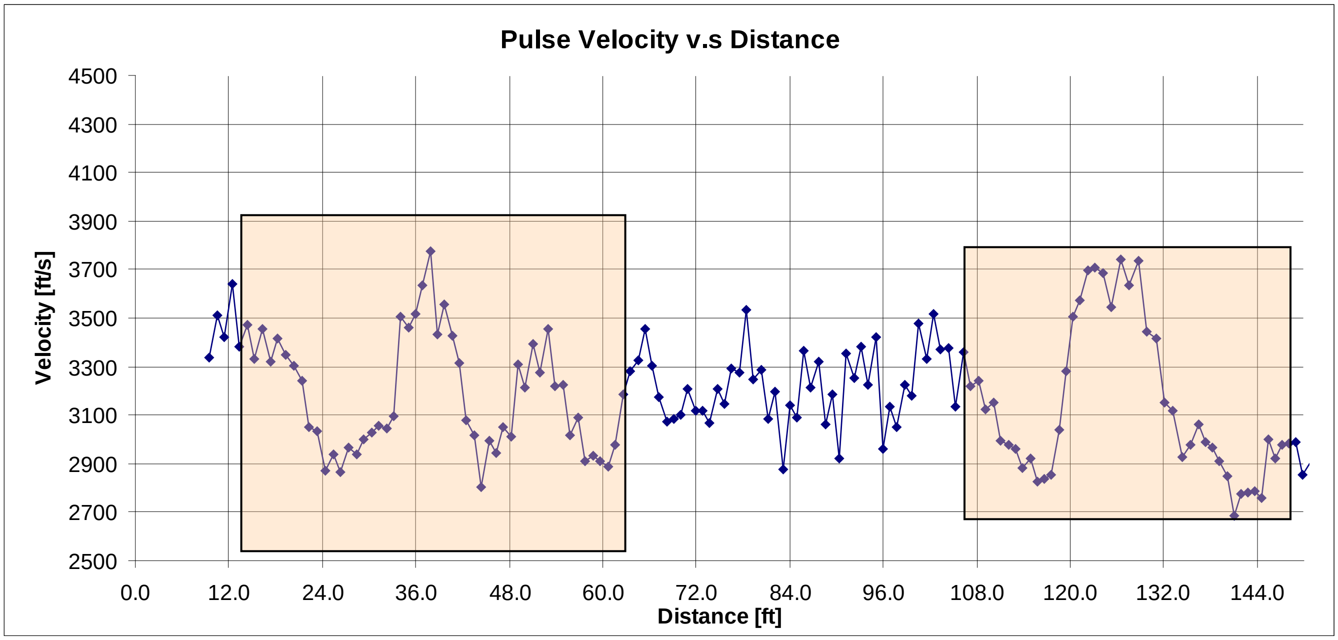


Figure 5.1: Acoustic Profiles from 0ft – 150ft

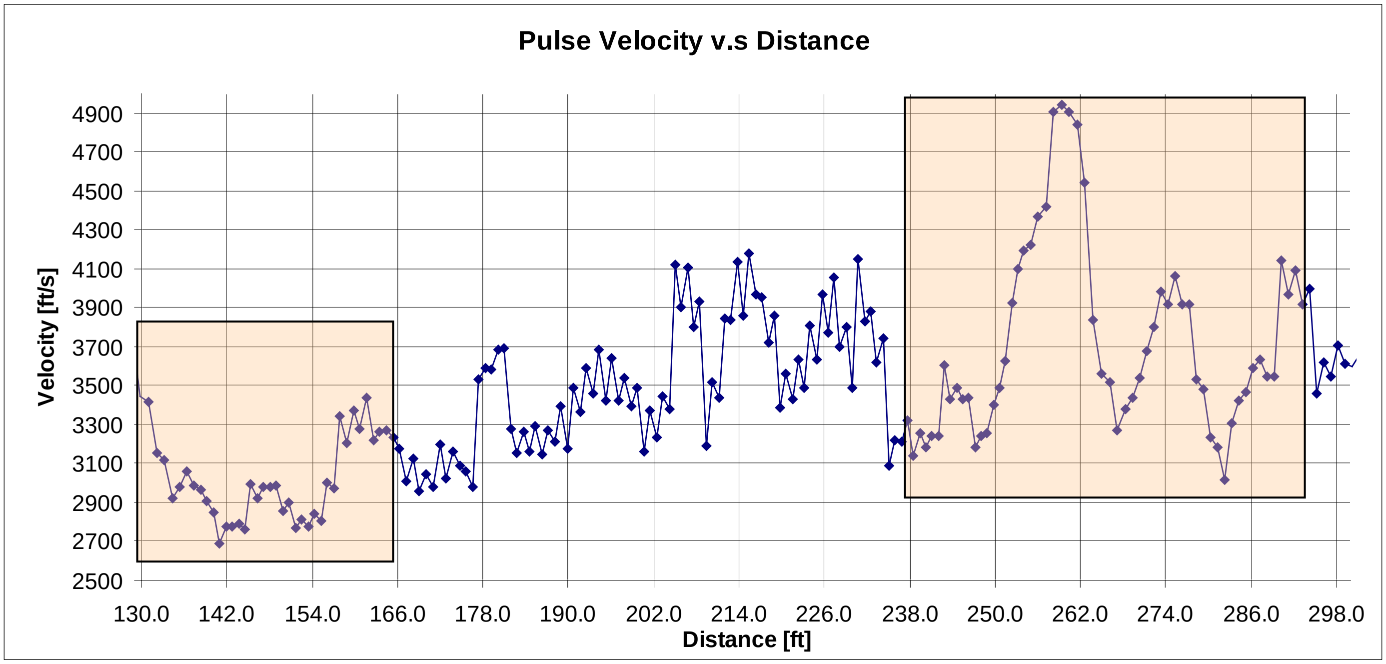


Figure 5.2: Acoustic Profiles from 130ft-300ft

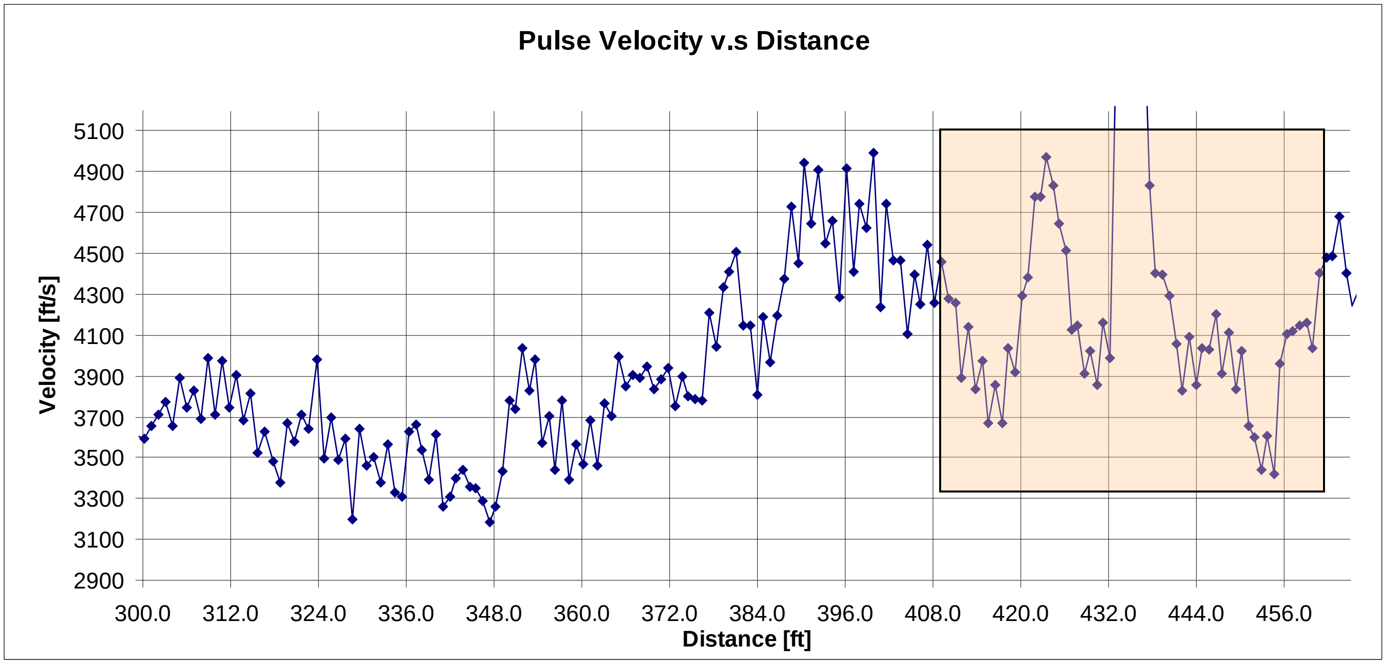


Figure 5.3: Acoustic Profiles from 300ft-465ft

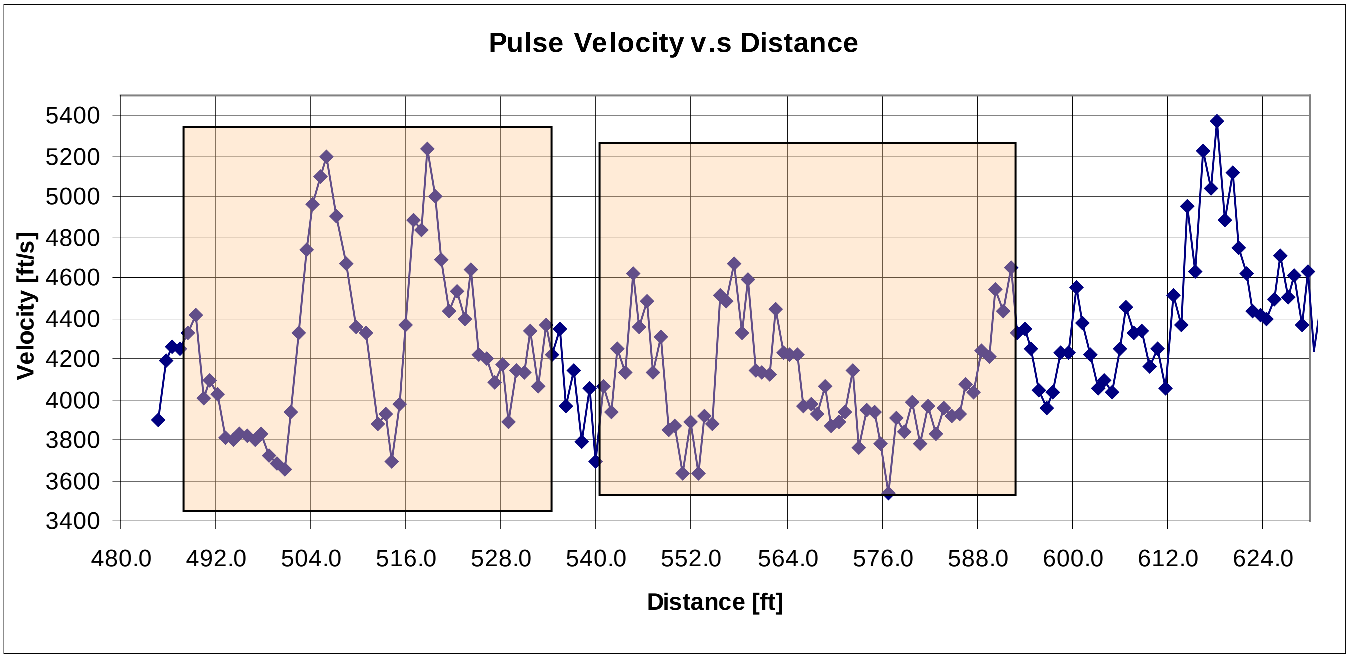


Figure 5.4: Acoustic Profiles from 480ft-630ft

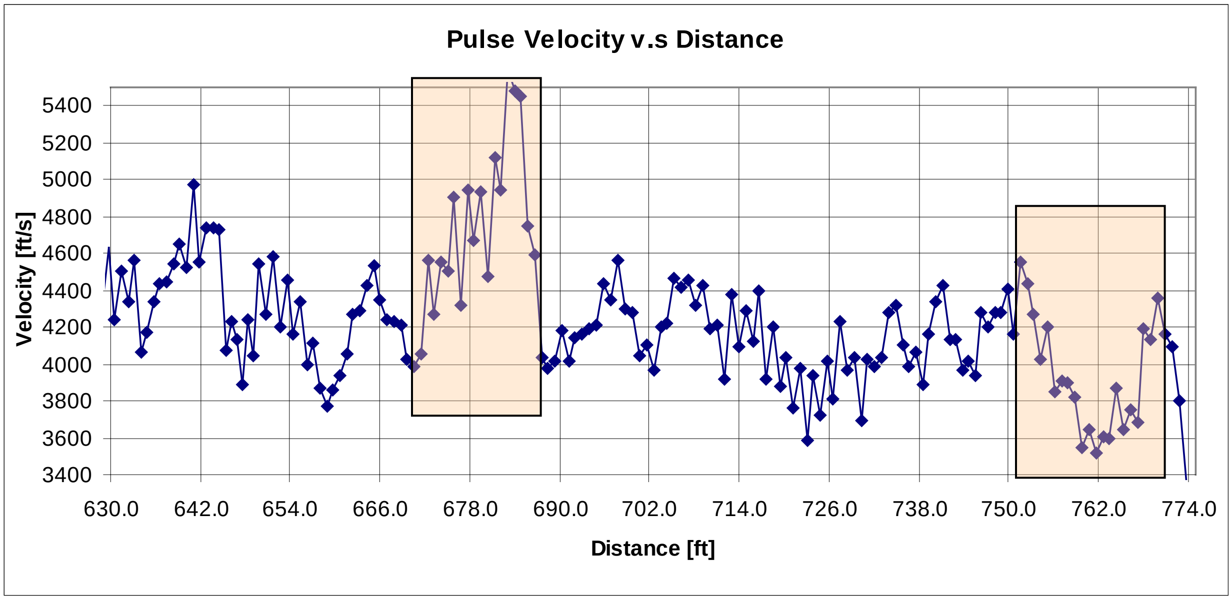


Figure 5.5: Acoustic Profiles from 630ft to 775ft

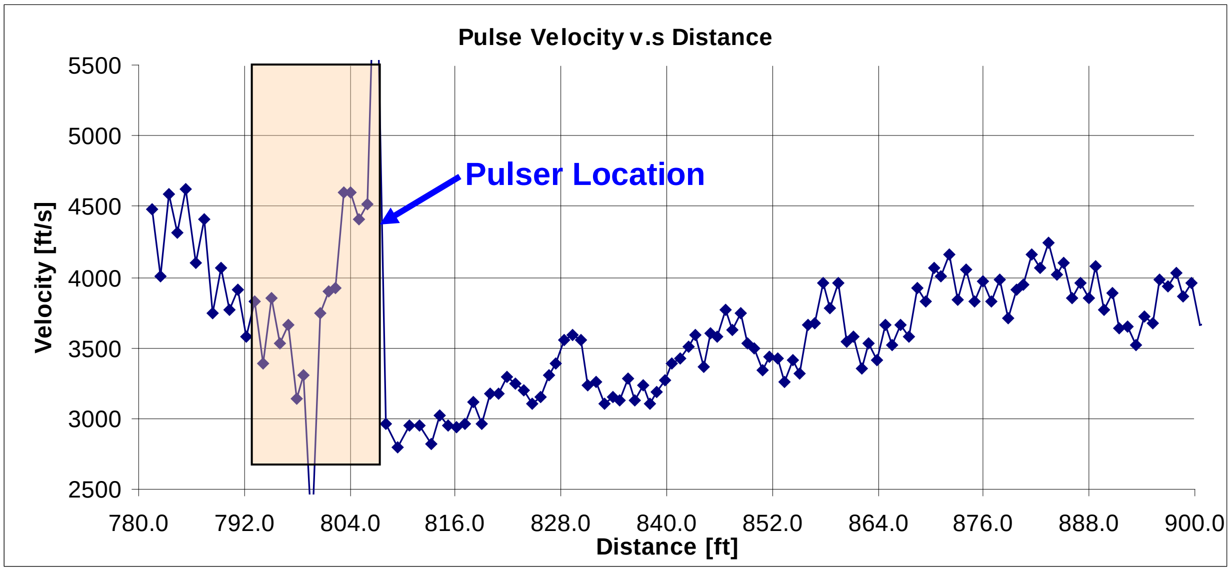


**Figure 5.6: Acoustic Profile from 780ft to 900ft**

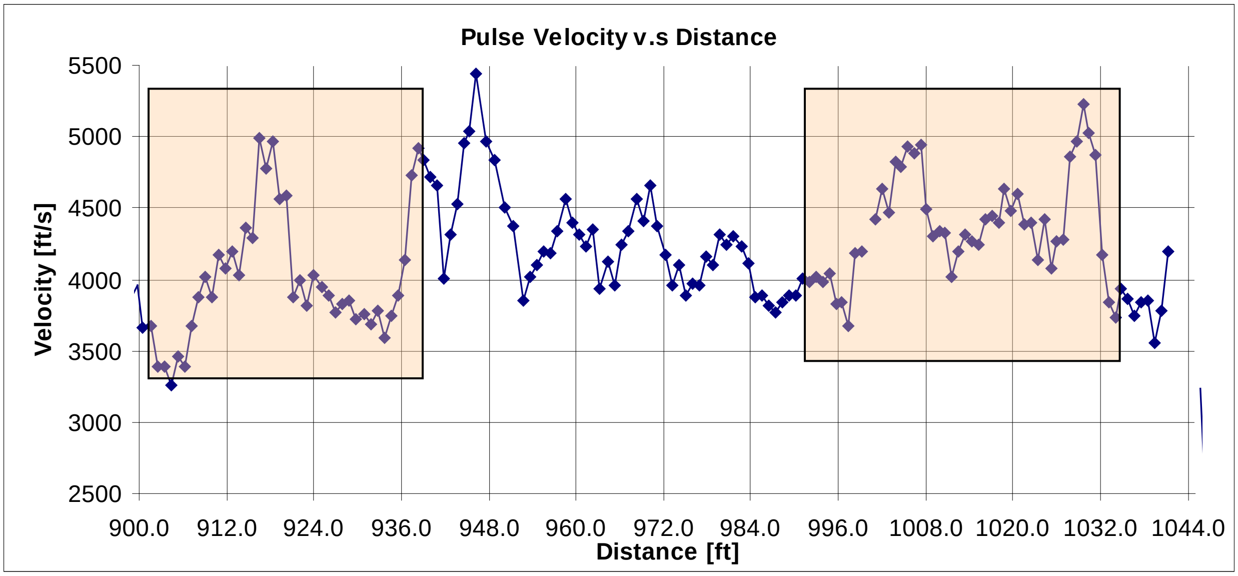


**Figure 5.7: Acoustic Profile from 900ft to 1050ft**

The data obtained by the SmartBall™ PWA pipe wall assessment tool suggest that there exist several interesting variations in the apparent pulse velocity at different points along the pipeline. It is not known whether or not the data reveal actual changes in the hoop stiffness of the pipe wall, or if the data has been affected by the existence or condition of the mortar lining or other pipe stiffness enhancements (such as previous repairs along the pipeline).

The data obtain from the SmartBall PWA tool also suggests that it is capable of detecting features on the pipeline such as valves and joints. The peaks presented in Figure 5.8 illustrate the location of the joints. As shown, a typical joint section for this pipeline is approximately 12ft.

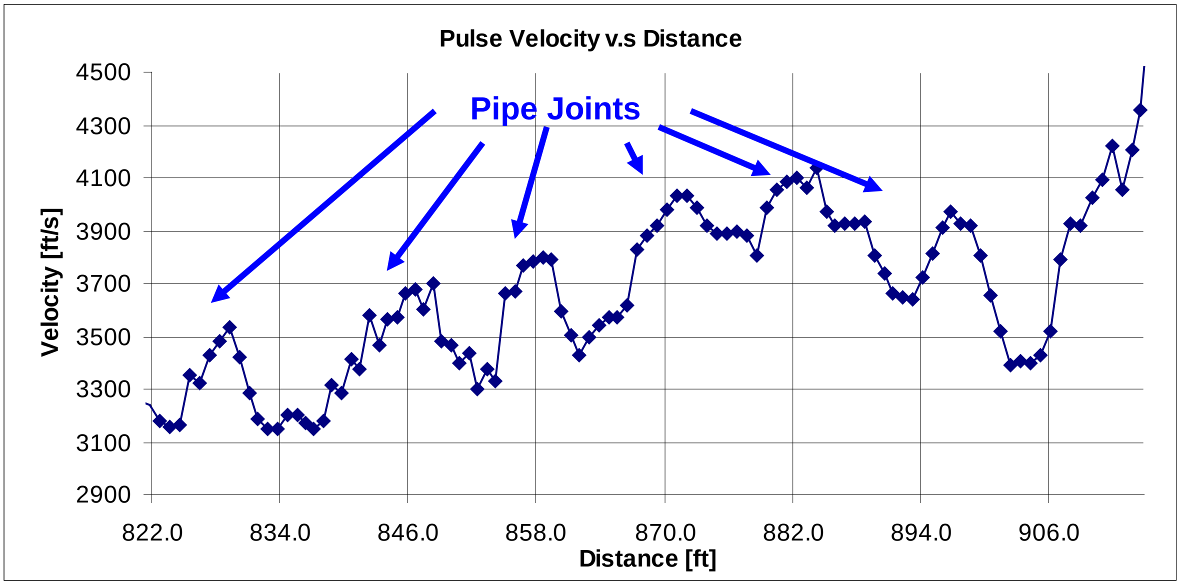


Figure 5.8: Joint Locations

The anomaly shown in Figure 5.9 illustrates the acoustic representation of the drain valve found at approximately 260 ft from the insertion location.

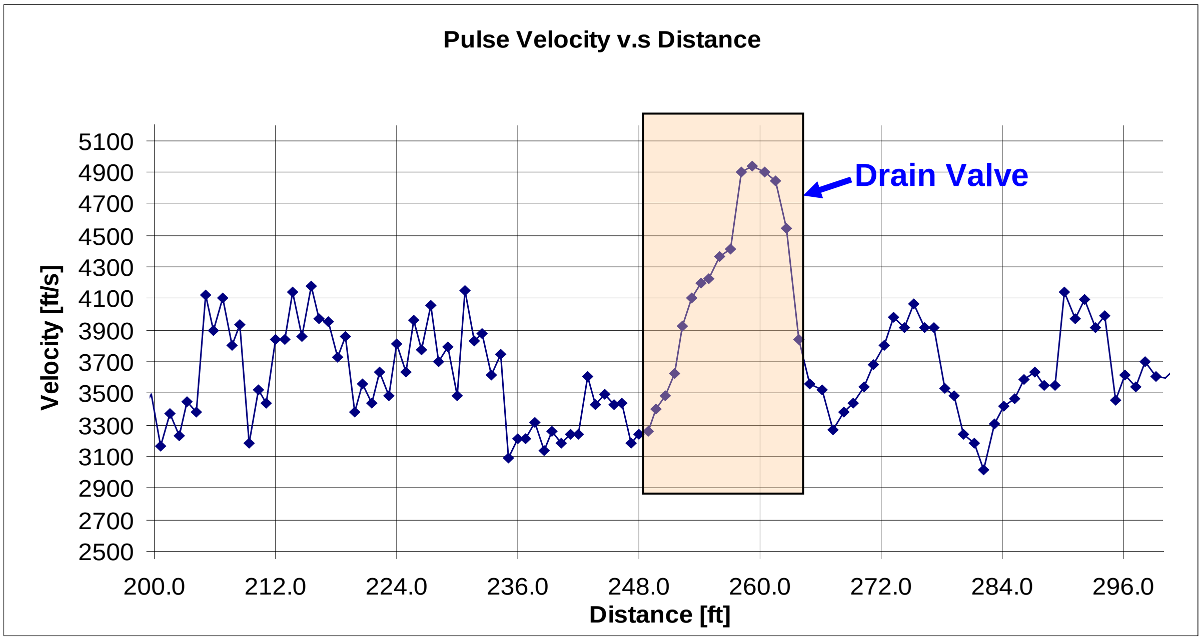


Figure 5.9: Drain Valve Location as Seen By Acoustic Pulses

The SmartBall™ PWA tool is capable of revealing variance and trends that can be later assessed by other means. The spatial resolution of the tool was approximately 1 data point every 2 feet which was unlikely to reveal individual pits, but may reveal areas where clusters of pitting or thinning produce weakening reaching over several feet along the pipe.

Confirmation of the areas of weakness will await excavation and inspection data, which in the case of this Louisville survey, are expected later this year.

# 6.0 Summary

Pure Technologies Ltd. is in the process of testing equipment and methods to do pipe wall assessment simultaneously with the operation of its SmartBall™ leak detection technology. In partnership with the Environmental Protection Agency and Battelle Memorial Institute, Pure Technologies was given the opportunity to conduct leak detection and pipe wall assessment on a waterline in Louisville Kentucky. Results indicate variances in the propagation velocity of low frequency acoustic pulses that may have resulted from variances in the hoop stiffness of the pipe. The simultaneous detection of 15 leaks including all three simulated leaks with the same instrument at the same time as the SmartBall™ PWA was functioning demonstrates the practical nature of the device and method.

# Appendix A: Ball Tracking Sensor and Pulser Locations

Sensor and Pulser Locations for August 6th and 7th, 2009 Inspections

| | | |
|---|---|---|
| AGM Location ID | Insertion |  |
| Latitude | 38.2536 | |
| Longitude | -85.6549 | |
| Distance from Launch | 0.0 ft | |

| | | |
|---|---|---|
| AGM Location ID | Midpoint Sensor |  |
| Latitude | 38.2547 | |
| Longitude | -85.6525 | |
| Distance from Launch | 809.0 ft | |

| | | |
|---|---|---|
| AGM Location ID | Extraction |  |
| Latitude | 38.2566 | |
| Longitude | -85.6489 | |
| Distance from Launch | 2057.0 ft | |

APPENDIX D

# Condition Assessment Field Demonstration

## Echologics Engineering Inc.

This report outlines the results of non destructive condition assessment testing performed on 24 inch concrete lined cast iron cylinder pipe in Louisville, Kentucky.

50 Ronson Dr, Unit 155
Toronto, Ontario, M9W 1B3

## Summary

The purpose of this study is to assess the performance of Echologics proprietary non-destructive acoustic condition assessment technology for leak detection and condition assessment on cast iron pipes. Data acquisition was performed on a 24-inch cast iron pipe that runs beneath Westport Rd in Louisville Kentucky on August 11th and 12th 2009. This report summarizes the results of the data acquisition and the corresponding analysis.

## Acknowledgements

***Battelle***

Abraham Chen – Program Manager

Bruce Nestleroth – Research Leader

Lili Wang – Program Assistant

***Louisville Water Company***

Keith Coombs – Program Manager

## Revisions

| | | |
|---|---|---|
| 0.1 | Sept 7, 2009 | Dave Johnston – Draft Report |
| 0.2 | Sept 18, 2009 | Ellen Turner – Draft Report Revision |
| 0.3 | Sept 25, 2009 | Marc Bracken – Draft Review |
| 0.4 | Sept 30, 2009 | Dave Johnston – Draft Submittal to Client |
| 1.0 | Nov 4, 2009 | Dave Johnston – Final Revision |
| 1.1 | Nov 13, 2009 | Dave Johnston – Update |
| 1.2 | August 2, 2012 | Dave Johnston – Results Update (for spun cast iron) |
| 1.3 | Nov 22, 2012 | Dave Johnston – Error Correction |

# Contents

## Figures

## Tables

# 1. Introduction

Echologics Engineering was invited to conduct a pilot study on selected cast iron pipes in Louisville, Kentucky. The intent of the study is to test the feasibility of Echologics proprietary non-destructive condition assessment technology both for condition assessment and leak detection on a 24-inch spun cast iron pipe along Westport Rd.

Data acquisition was performed on several sections of the 24-inch main. There are three sets of results presented in this report. First, the results of the background leak detection results will be discussed. Locations of any already existing leaks will be presented in this section. Second, the results of the leak detection demonstration will be presented. This will include whether or not the demonstration leak was discovered and what the estimated flow rate is. Finally, the results of the condition assessment will be presented.

Background measurements were performed in section lengths between 250-feet and 360-feet in length. The background measurements were performed with the purpose of finding any already existing leaks and performing the condition assessment measurements. Typically, the same methods are used when Echologics is performing commercial assessment services.

The demonstration measurements were performed using different sensors (hydrophones) and longer section lengths, approximately 1000-feet. Again, this arrangement was chosen because it would be typical for commercial leak detection projects.

As a warning to the reader, it should be noted at the outset that for completeness, we have included fairly extensive technical information, some of which will be beyond the technical knowledge base of some of the readers of this report. It is not our intent to educate readers in signal processing theory, although we have provided some layman’s explanation of the background theory.

# 2. Background

## 2.1. Signal Processing

Time differences are measured using fast Fourier transforms (FFTs) and advanced cross-correlation algorithms. There are also a number of other acoustic tools that aid in data analysis processes. For the purposes of understanding this report, there are several signal processing functions that should be understood:

Coherence Function: The coherence function is a measure of how similar the vibration signals are on a frequency basis. When two signals are perfectly similar at a given frequency (for example, two sine waves), the coherence function value is 1 at that frequency. Good coherence would be considered anything at 0.5 and above.

Transfer function: The transfer function is a frequency based plot of the relative strength of the two measurement channels. This function shows the relative vibration level of the blue and white stations, and can be given in log or linear format. Many vibration engineers prefer to see both formats, as a log plot is easier on initial read, however a linear plot will show more detail.

Frequency plot (FFT): The frequency plots given in this report are fast Fourier transforms of the raw level vs. time signals. Very simply, these plots show the frequency content of the vibration signals measured. It is often possible to pick out leak noise on the frequency plots, and these can be used to analyze the leak detection signals. For example an FFT from the blue station may show a spectrum consistent with leak noise with significant higher frequency vibration, while the white station signal may show no high frequency content indicating a possible PVC repair (the PVC repair may filter out high frequency content).

Correlation Function: The correlation function is the level vs. time function that will indicate a leak, and in the case of condition assessment measurements will show the out-of-bracket peak or time difference. Ideally a good correlation peak should be very sharp, and very prominent. The LeakfinderRT software will present a warning for an out-of-bracket signal when the time delay of the signal approaches the total time delay of the entire measurement distance (i.e when t⇒d/v).

## 2.2. Leak Detection

The leak detection methodology used is the cross correlation method. A correlator listens passively for noise created by a leak. Two sensors are mounted on fire hydrants, exposed pipe, or valves in such a way that the leak lies between them, or is ‘bracketed’ by the sensors. A leak that lies outside the area spanned by the sensors is known as an ‘out-of-bracket’ leak. Any active leaks or draws or other sources of noise on the pipe will vibrate the pipe and detected by the sensors.

The signals will be recorded and the cross-correlation plot will be analyzed. Any potential leaks will appear as a spike in the cross-correlation plot. The position of the spoke on the x-axis corresponds to the time difference it takes for the signal to arrive at the Blue and White stations. The wave velocity is known and therefore the position relative to either of the stations can be computed.

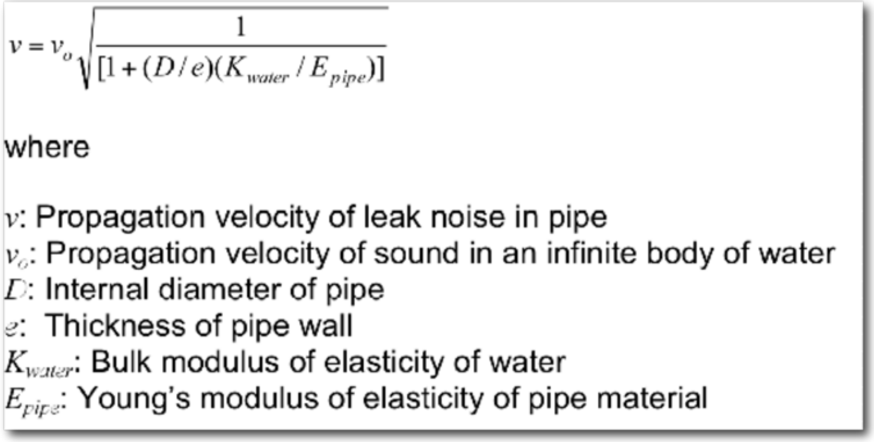
## 2.3. Non-Destructive Condition Assessment

An acoustic signal induced in the pipe may be used to determine the acoustic wave velocity in a section of pipe, which can in turn be used to back calculate the average wall thickness of the pipe. Knowing the distance between two sensors mounted some distance apart on valves or fire hydrants, the acoustic wave velocity will be given by v = d/t, where d is the distance between the sensors, and t is the time taken for the acoustical signal to propagate between the two sensors. If an accurate measurement of the acoustic wave velocity is made, it is possible to back-calculate the remaining average thickness of the pipe between the two sensors.

*The wall thickness measured represents an average between the two sensors.* Typically the length of the pipe section over which the acoustic velocity is measured 100 to 300 metres *(300’-1000’)*, however this distance can be decreased to anywhere between 30-100 m to increase the resolution.

Echologics proprietary leak noise correlator, LeakfindeRT was used to determine the acoustic velocity. An acoustic source outside the area spanned by the sensors (an 'out-of-bracket' source) was used to induce an acoustic wave in the pipe, and the time delay difference was measured. At each site the noise source to induce the acoustic wave; was either operation of a fire hydrant, or a valve or hydrant was impacted.

*The average wall thickness of the pipe section between the acoustic sensors is then back calculated from a theoretical model. As the pipe wall thickness decreases over time, the acoustical wave velocity decreases. From an intuitive perspective, this is akin to trying to run on a trampoline versus solid ground; as the bounding layer becomes more flexible the propagation velocity decreases. The acoustical wave velocity is given in* Equation 1: Wave Velocity - Thickness Model *below.* It should be noted that there are other factors that affect the propagation velocity such as water temperature and pipe wall inertia. These factors are not shown here but have been accounted for in the final results.



$$v = v_o \sqrt{\frac{1}{[1 + (D/e)(K_{water}/E_{pipe})]}}$$

where

$v$: Propagation velocity of leak noise in pipe
$v_o$: Propagation velocity of sound in an infinite body of water
$D$: Internal diameter of pipe
$e$: Thickness of pipe wall
$K_{water}$: Bulk modulus of elasticity of water
$E_{pipe}$: Young's modulus of elasticity of pipe material

**Equation 1: Wave Velocity - Thickness Model**

The acoustic propagation wave (the water hammer mode) propagates as a compression wave in the fluid, and a dilatational wave in the pipe. Therefore the *pipe will breathe on a microscopic level, and therefore the pipe will go into stress*. There are two key implications to this:

1. Only the structural part of the pipe that can carry load will contribute to the structural stiffness of the pipe, therefore deposits on the pipe wall such as tuberculation or graphite will not be included in the average wall thickness measurement.
2. We will measure the minimum structural thickness of the pipe, as the level of strain of the pipe will be dependent on the minimum wall thickness at any point around the circumference the pipe.

As noted, the pipe wall thickness calculated from these measurements represents an average value for the pipe section over which the acoustic velocity is measured. At first glance, this may appear to be a limitation of the technology, as the question could be reasonably asked as to whether the method can find pockets of corrosion. In practice this has not been the case. The technology has been applied to generally much greater sample lengths *of pipe than could be done with random sampling or electro-magnetic technologies. Therefore when surveying long lengths of pipe, the operators begin to look for anomalies in the measurements that could indicate degraded sections of pipe. When these are seen, the* distance between the sensors may be *decreased and more resolution* obtained. Generally, pipes will have a more-or-less uniform thickness profile with isolated pockets of corrosion over significant lengths, say 50 to 100 meters, as soil and bedding conditions are unlikely to change significantly over such distances. Also, average wall thickness values are *suitable to evaluate the residual life of pipes for the purpose of long-term planning of rehab and replacement needs.* The use of techniques such as evaluation of stray currents, and soil corrosivity studies and main break history may be used in conjunction with our data to evaluate overall pipe condition.

## 2.4. Metallic Pipe

The primary degradation mechanism in buried metallic pipes is corrosion. Corrosion occurs in many different forms and can be accelerated or inhibited based on soil properties, water properties and characteristics of the pipes surroundings.

Two main forms of corrosion occur in buried pipelines: uniform corrosion and pitting corrosion. Uniform corrosion occurs when general, constant corrosion occurs on all surfaces of the pipeline. This can occur from the inside out and is caused by the properties of the water that the pipe is carrying. Or it can occur from the outside in if the pipe is in submerged or semi-submerged conditions.

Pitting corrosion occurs on the inside and outside surfaces of the pipe. This is when small areas corrode preferentially leading to cavities or pits, and the bulk of the surface remains unaffected. Pitting corrosion can be accelerated under stagnant conditions, which is why it is generally more severe on the outside surface of the pipe.

Other forms of corrosion can occur including: galvanic (dissimilar metals), De-Alloying (graphite), inter-granular and erosion corrosion. All of these can contribute to the overall degradation of the pipe but they are considered to be relatively insignificant compared to the impact of uniform and pitting corrosion.

## 2.5. Concrete Lining

The wave propagation velocity is a function of the thickness of the pipe wall and the corresponding material elastic modulus. Therefore, if a pipe is concrete lined the structural stiffness of the pipe is increased via the addition strength of the concrete. The wave velocity then becomes a function of the structural stiffness of the metal and the concrete lining.

In order to account for this, it is necessary to calculate the nominal thickness of the pipe as if it was not lined with concrete i.e. the equivalent structural thickness of a metallic pipe without the concrete lining. This will be referred to as the equivalent thickness and generally it is 2–3mm thicker than the thickness of the base metal. This value can also be considered as the ‘effective’ or the ‘structural’ thickness of the pipe.

The measurement will then be compared to this value, the equivalent thickness rather than the thickness of the metal alone.

## 2.6. Nominal Data

Battelle provided original specifications for both diameters of pipe. The details are presented below in Table 1: Nominal Dimensions. There is also an image of the cross-section of the pipe shown in Figure 6: Pipe Wall Cross-Section. It closely matches the values presented here.

| YOI | Type | Dia (inch) | Dia (mm) | Cast Iron Thickness (inch) | Cast Iron Thickness (mm) | Lining Thickness (inch) | Lining Thickness (mm) |
|---|---|---|---|---|---|---|---|
| 1932 | Spun Cast Iron | 24 | 610 | 0.75 | 19.05 | 0.25 | 6.35 |
| | Equivalent Thickness of Cast Iron without Concrete Lining | | | | | | |
| | | = | 22.0 | mm | | | |
| | | = | 0.866 | inch | | | |

Table 1: Nominal Dimensions

## 2.7. Sensitivity Analysis

Echologics has committed a substantial amount of effort to reduce sources of error in our assessments. However there are still variables that strongly affect the final result. They are as follows:

### Distance Measurement

A calibrated wheel is used for obtaining our distances, and distance measurements were repeated 3-4 times for each location to ensure the best possible accuracy. For example, on a total distance of 150m, an error of +2.5m resulting in a measured distance of 152.5m will cause a positive error in the final result of approximately 17.5%. An accurate distance measurement is therefore crucial to an accurate assessment. For this reason, our preference is always to use line valves, as these provide the most accurate distance measure, as it is a point-to-point measurement. If the pipe has multiple bends and elevation changes between the sensor connection points, error in the distance measurement increases, as it is not always easy to identify where the bends occur.

### Pipe Manufacturing Tolerances

The pipe laid will have small differences in thickness and due to manufacturer and tolerances. This factor is usually 5-10% dependent on the manufacturer and the material. This may lead to a pipe growing by a small percentage (5-10%) compared to the nominal thickness used. This is particularly true of the older vintages of pipe measured in this study. Generally, the materials data used for the calculation is chosen using conservative estimates. The purpose of this is to provide a worst-case scenario to the client i.e. assume that the pipe is manufactured to the better side of the tolerances and calculate the remaining thickness based on this. This is not considered to be error because the presented result actually represents the current condition of the pipe.

Variation in internal diameter of the pipe can also affect the final result. If the manufacturing tolerances for the diameter are approximately 5-10% the corresponding results on the calculated value will also vary by approximately 5-10%. This is considered to be relatively insignificant if, in fact, the information provided by the client is correct. This is not always the case and it will be discussed later in this section.

### Repair Clamps on Previous Leaks

A small number of repair clamps should have an insignificant effect on the test results, since the acoustic wave is primarily water borne and will bypass the clamps. It should be noted that although the acoustic wave is primarily water-borne, it is a coupled wave that moves simultaneously in the pipe (in an axi-symmetrical breathing mode), and in the water as a compression wave. Thus the wave will generally skip across discontinuities such as clamps, and reestablish itself in the pipe material beyond.

### Variation on Young's Modulus

In general, a change in elastic modulus of 10% will cause a change in the calculated thickness by approximately 10%. Therefore it is necessary to account for this variation. The elastic modulus is known for common materials used in the manufacturing of pressure pipe but this value can vary from manufacturer to manufacturer. This depends on the manufacturing process and the quality of the material.

### Replacement of short Pipe Sections for Leak Repairs

The effect of short pipe replacements will depend on the material used. For example, a new 6-metre long ductile iron repair in a 100-metre long / 152 mm-diameter cast iron pipe section of average condition, will produce a small error of +3.5% in predicted wall thickness. However, the same repair made with PVC pipe would produce an unacceptable error of -41%. Preferably, pipe sections selected for testing should be free of repaired segments. However, if this condition does not exist, the effect of new pipe segments can be accounted for provided that accurate information is available for the location, length, material type and class of new pipe segments.

### Inaccurate Records

In some cases the possibility exists that inaccurate information was provided by the client, specifically referring to the pipe diameter and the pipe material. As described above, small manufacturing variations in elastic modulus and internal diameter only affect the final result by 5-10% but if the information supplied by the client is incorrect, it is flawed by much greater magnitudes. For example, a common error would be to mistake a 200mm pipe for a 250mm pipe. When the calculation is performed using an internal diameter of 250mm, the remaining thickness may be 12.5mm. If the same calculation is performed using an internal diameter of 200mm, the remaining thickness is reduced to 9.3mm, a change of 3.2mm! In this case, the error caused a 35% over estimation of the pipe wall thickness.

Another common problem arises when improper pipe material information is provided. For example, if a pipe was thought to be spun cast iron when, in fact, it is ductile iron. When the calculation is performed using the elastic modulus for spun cast iron (131Gpa), the remaining thickness may be 11.6mm. If the same calculation is performed for a ductile iron pipe (169Gpa), the remaining thickness drops to 8.9mm, a change of 2.7mm! The error caused a 30% over estimation of pipe wall thickness.

It becomes obvious that accurate records from the client are an essential requirement for providing accurate condition assessment results.

## 2.8. Sources of Error

The results of the sensitivity analysis provide insight into how the various material properties and pipe dimensions can affect the final result. If one ignores error introduced by manufacturing tolerances and inaccurate nominal information, the main source of error is cause by improper sensor-to-senor distance measurements.

The average section of pipe tested during this project was 150m. If one assumes that the sensor-to-sensor spacing can be measured accurately to within 1m, the resulting error in the thickness calculation is approximately 5%. If however, there are multiple bends in the pipe or significant elevation changes, the error in the distance measurement may increase. For example, one bend in the pipe may introduce an additional error of 1m. With a total distance error of 2m, the resulting error in the final calculation is approximately 10%.

## 2.9. Negative Correlation Signals

There were several locations where correlation signals could not be acquired, or they were of poor quality. This can happen for a number of reasons, and we typically find that this occurs on a percentage of all of our projects. Although we have never had the opportunity to fully explore the reasons for this, the following are some of the conditions that we have encountered that have affected our measurements:

1. The presence of plastic repairs in metallic pipes can cause poor correlation signals, and will also cause inaccurate thickness

2. Loose or worn components in fittings used for the measurements, such as valve or hydrant stems.

3. Heavily tuberculated pipe, particularly old cast iron or unlined ductile iron may attenuate the acoustic signals to such an extent that a correlation is of very low quality.

## 2.10. Condition Assessment Data Interpretation

The condition of a pipe may be assessed based by judging it based on other pipes that we have measured and then exhumed to determine the condition. For a full condition assessment, it is recommended that our data be used in conjunction with soils information, any ground potential measurements done, along with any pipe samples exhumed during leak repairs. Acoustic non-destructive condition assessment cannot pinpoint the source of degradation. For example, a reading of -20% pipe wall could mean that the pipe is generally degraded along it's entire length, or the pipe could have significant degradation at only one or two locations.

In the absence of other parameters, we have provided a gradation scale based on our previous project experience and pilot studies. Based on our previous experience, we have provided background on typical results found during the course of our condition assessment surveys. Please note that the sample photos shown in the following section are from a previously performed pilot study. They are to be used only to demonstrate the typical levels of degradation found from previous testing. This is meant to act only as a guideline in assessing the results of this study.

The images presented below show four pictures in each. The top left picture shows the as-found condition of the pipe. The top right image shows an overview shot. The bottom left shows a close up of the surface after it was sandblasted. The bottom right shows the internal surface after it was sandblasted.

The descriptions below described results measured by Echologics, given by an averaged measured loss in percent. The physical results given are the average measured value at either end of the pipe, the average pit depth on the outside surface / inside surface and the qualitative condition on the outside surface / inside surface.

## 2.11. Results of Pipe with 5% degradation

A section of pipe where 4.7% measured loss is shown in Figure 1. The nominal thickness of this pipe was 12mm (0.47in), whereas the lab measured physical thickness at either end of the sample was 11.4+/-2.7mm (0.45in +/-0.1in). The average pit depth was 1.5mm / 1.9mm. The pipe was qualitatively described as very good / very good. This again is an indication that the acoustic wave velocity from the acoustic mode of the pipe that we are measuring is based on the average minimum structural thickness, not the average physical thickness.

The sample was taken from an area with corrosive clay based soil. The figures indicate that although there are local areas of corrosion, the pipe wall is generally in good condition. Based on this type of result, a pipe at this level of degradation may have occasional failures from corrosion holes but it is structurally sound.

### 2.12. Results of Pipe with 9% degradation

Figure 2 shows photographs of a section of pipe measured at 8.9% average loss. The physical thickness of this pipe was measured at 8.8+/-0.8mm (0.35in +/-0.03in)(nominal was 9mm), with average pit depth at 2.5mm / 3.0mm. The condition of the pipe was rated as very good / moderate. The corrosion of this pipe was primarily localized internally on the bottom of the pipe as can be seen in the right photo. The corrosion appeared in this case more continuous perhaps due to sediment build up at the bottom of the pipe. Overall the structural integrity of the pipe is good.

### 2.13. Results of Pipe with 47% degradation

Figure 3 provides photographs of a pipe with a measured 47.3% average loss of pipe wall thickness (11.0mm, 0.43in nominal). In the lab the average physical thickness was measured as 11.6+/-3.3mm (0.456in, +/-0.13in) and an average pit depth of 3.8mm / 2.5mm. The physical condition of the pipe was described as very poor / poor. Note that there were also numerous through holes in the pipe evident after sand blasting. It is interesting to note that the pipe was not leaking when measured, probably due to the build up of tuberculation.

Figure 1: Photos of pipe with 4.2% measured loss

Figure 2: Photos of pipe with 8.9% measured loss

Figure 3: Photos of pipe with 47.3% measured loss

### Guidelines for Interpretation of Results

Based on the results, we recommend the following guidelines for the interpretation of our data:

- 10% or less: The pipe is in very good condition, but may still have minor levels of uniform corrosion. Some localized areas of pitting corrosion may exist but it is expected that the areas are isolated.
- 10-20%: Pipe is in good condition, there may be some moderate uniform surface or internal corrosion, or more localized areas of pitting corrosion.
- 20-35%: Pipe may have significant localized areas of pitting corrosion, or moderate uniform corrosion throughout.
- >35%: Pipe is in poor condition and may have numerous areas of pitting corrosion, including significant uniform thinning of the pipe.

# 3. Methodology

## 3.1. Leak Detection

In general, it is more challenging to survey for water main leaks with a leak noise correlator than using it to pinpoint a leak, which is known to exist, as there will be a high incidence of negative (no leak) results. When many negative results are encountered, the surveyor may begin to question the operation of the equipment, or his procedures. Therefore, one of the main issues with testing pipes where there is no known leak is to ensure that the proper steps are taken to ensure that the results are properly analyzed so that the presence (or lack of) a leak may be definitively decided. Based on our previous experience with leak detection surveys, and our familiarity with acoustic technology, procedures were implemented for both on site, and follow-up analyses were performed in order to make a definitive decision on whether or not a leak was present.

1. Sensors were attached on valves or hydrants as available at each site. Where measurements were performed on valves, the sensors were placed on the tops of valve keys that had been lowered onto the valves or placed directly on the valve nut when possible (if the valve chamber was clear of debris).

2. The LeakfinderRT radio channels are color-coded blue and white, where blue is always the right audio channel and white the left. For all measurements, the locations of the blue and white channel were noted.

3. In general, all leak detection measurements were taken on the same segments of pipe where the condition assessments were performed.

4. After placement of the sensors on the appropriate valve or hydrant, the fitting was tapped, and listened to at the radio receiver to ensure that the sensor was functioning, and that the radio signal was arriving properly at the receiver. This is called a scratch test.

5. Where possible, sensor spacing was accurately measured using a calibrated measuring wheel.

6. A correlation measurement was performed, and the signal was saved to the computer, so that further analysis could be performed later in the office, and so that the client could have a permanent record of the raw noise file if needed.

7. Where a positive signal was detected (a correlation peak with good signal coherence), the location was immediately checked to determine if it corresponded to a service line or other notable draws from the pipe. If this was the case, several more correlations were conducted to see if the ‘usage’ stopped.

8. Where negative results were obtained (no clear correlation peak was obtained), a series of checks was completed, including a review of coherence and of the blue and white frequency spectra, to detect the presence of a PVC repair or some other anomaly in the test section. Such checks have become part of our protocol for leak detection surveys.

## 3.2. Condition Assessment

The following survey methodology was used:

1. For each location surveyed, the distance between the sensors was measured. A very accurate measurement of the distance between sensors is required. Although less important for leak detection measurements, an error in measurement of even 3 feet over a 300 foot distance can lead to errors of 15% in wall thickness estimation. The margin of error acceptable will be dependent on the pipe type and the distance between sensors. Typically, for a cast iron pipe, we have not found it difficult to obtain this measurement accuracy. There were some cases where accurate pipe geometry was not available. For example, elevation changes and curves in the road may create discrepancies between our distance measurement along the surface and the physical distance of the pipe underground. Any locations that presented this difficulty were noted and will be discussed in the final results.

2. Sensors were placed on the fittings, either hot taps that were previously installed or in potholes on the surface of the pipe, and a noise source was created, typically at a location out-of-bracket (beyond one of the sensors). The noise sources were either a running well, light impacting on valves or use of the shaker. Some sites permitted the use of all 3, others were limited to 1 based on space restrictions

3. The temperature of the water was recorded, generally at the time of testing, for each of the test sites.

4. The data was stored as a raw wave file for further analysis and confirmation in our offices. Data was reanalyzed and filtered to obtain an optimum correlation peak.

## 3.3. Instrumentation

The leak detection was completed using Echologics' proprietary leak detection system, LeakfinderRT. The system works by placing sensors on two water system fittings such as valves or hydrants bracketing the leak. If a leak is present, the software then uses the time difference it takes the leak noise to reach the two sensors to pinpoint the leak location. The sensors used for the purposes of this project were surface mounted, either on hydrant flanges, hydrant secondary valves or line valves. There were two types of sensors used in this study:

- Echologics’ proprietary Hydrophones for direct measurement of the water column
- Echologics’ piezoelectric accelerometers, with a sensitivity of 1 V/g

Each sensor has its own specific attributes that make it preferable in certain situations. The Hydrophone is particularly well suited to measuring asbestos cement and medium to large diameter mains (12in and larger), as leaks on these pipes generally are dominated by lower frequency content (200Hz and below). The standard piezoelectric accelerometer has a slightly higher noise floor, and has better high frequency response, making them more suitable for some measurements on smaller diameter (10in and lower) metallic pipes that typically have higher frequency content (200 Hz and higher). Radios used were 460 MHz or 433 MHz analogue units manufactured by Echologics.

# 4. Results and Discussion

First, general information regarding the site location and the pipe will be discussed. Following this, the results of the demonstration will be presented first, followed by the results of the background measurements and the corresponding condition assessment. A map showing the site location and the general layout can be found in Figure 7: Site Layout.

Table 2: Excavation Locations presents a list with the locations of the excavation pits. It shows the approximate distance between pits and a corresponding description of the type of excavation. The distances presented were not the same distances used when performing data analysis.

For the Leak Detection Demonstration, the pipe was broken up into three longer sections. For the Background and Condition Assessment measurements the pipe was broken up into seven sections. More sections were chosen for the assessment measurements in order to provide a better representation of the pipe condition.

**Pipe excavation locations**

EPA technology Demonstration

| ID | Distance Feet | Name | Type |
|---|---|---|---|
| **1** | 0 | Lauch Pit | 6x8 with trenchbox, 12" T, Reducer |
| **A** | 250 | Sensor Pit A | 3x3 to top of pipe |
| **B** | 510 | Sensor Pit B | 3x3 to top of pipe |
| **4** | 581 | Corp Valve **1 &2** | 6x8 with trenchbox, stone backfill |
| **C** | 809 | Sensor Pit C | 3x3 to top of pipe |
| **2** | 1080 | Corp Valve **3 4 5 & 6** | 6x8 with trenchbox, stone backfill |
| **D** | 1173 | Sensor Pit D | 3x3 to top of pipe |
| **E** | 1439 | Sensor Pit E | 3x3 to top of pipe |
| **5** | 1580 | Corp Valve **7 & 8** | 6x8 with trenchbox, stone backfill |
| **F** | 1750 | Sensor Pit F | 3x3 to top of pipe |
|  |  | Fire Hydrant | Pressure gage |
| **3** | 2057 | Receive Pit | 6x8 with trenchbox, 12 inch T, Reducer |
|  | 2100 | 12" Discharge |  |

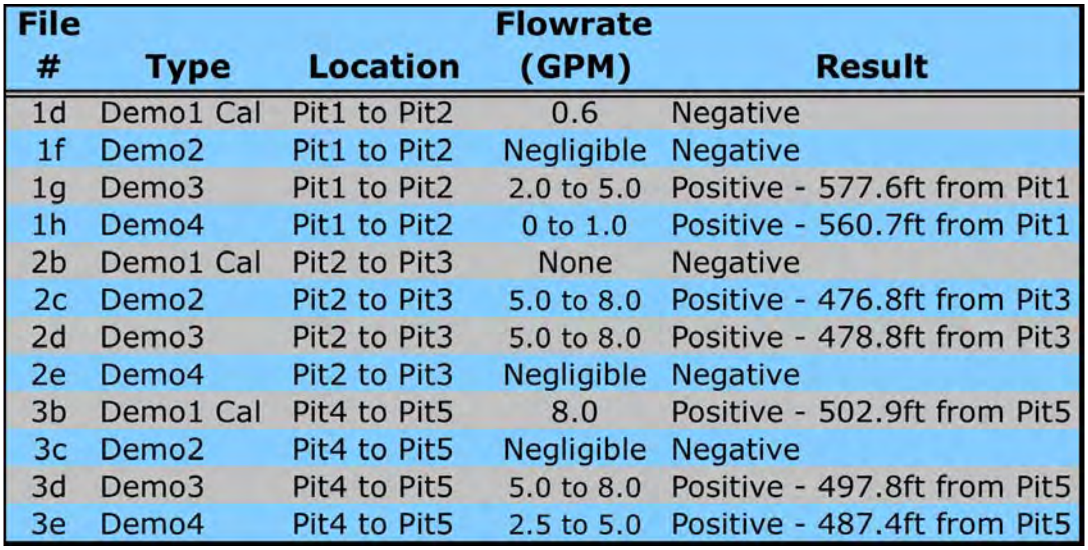
Table 2: Excavation Locations

| Location | Sensor-to-Sensor Spacing (ft) |
|---|---|
| Pit1 to Pit2 | 1080.7 |
| Pit2 to Pit3 | 979.3 |
| Pit4 to Pit5 | 1001.6 |
| Pit1 to PitA | 250.7 |
| PitA to PitB | 260.5 |
| PitB to PitC | 298.6 |
| PitC to Pit2 | 271 |
| Pit2 to PitE | 360.9 |
| PitE to PitF | 294.6 |
| PitF to Pit3 | 312.7 |

Table 3: Sensor-to-Sensor Distances

## 4.1. Demonstration Results

The results of the demonstration tests are presented below in Table 4: Demonstration Results. The column titled File # corresponds to the WAV file number in the name of the file when it was recorded. It can be cross-referenced with the screenshots presented in the Appendix. The column titled Type corresponds to the type of test that was provided by Battelle. At each location there was four demonstrations the first of which, Demo1 Cal, was a calibration test where the induced flow rate was known. The column titled Location presents where the sensors were attached to the pipe. The column titled Flowrate (GPM) presents either the known flow rate for calibration tests or the estimated flow rate for the others. The column titled Result presents the outcome of the correlation measurement, either negative or positive.



| File # | Type | Location | Flowrate (GPM) | Result |
|---|---|---|---|---|
| 1d | Demo1 Cal | Pit1 to Pit2 | 0.6 | Negative |
| 1f | Demo2 | Pit1 to Pit2 | Negligible | Negative |
| 1g | Demo3 | Pit1 to Pit2 | 2.0 to 5.0 | Positive - 577.6ft from Pit1 |
| 1h | Demo4 | Pit1 to Pit2 | 0 to 1.0 | Positive - 560.7ft from Pit1 |
| 2b | Demo1 Cal | Pit2 to Pit3 | None | Negative |
| 2c | Demo2 | Pit2 to Pit3 | 5.0 to 8.0 | Positive - 476.8ft from Pit3 |
| 2d | Demo3 | Pit2 to Pit3 | 5.0 to 8.0 | Positive - 478.8ft from Pit3 |
| 2e | Demo4 | Pit2 to Pit3 | Negligible | Negative |
| 3b | Demo1 Cal | Pit4 to Pit5 | 8.0 | Positive - 502.9ft from Pit5 |
| 3c | Demo2 | Pit4 to Pit5 | Negligible | Negative |
| 3d | Demo3 | Pit4 to Pit5 | 5.0 to 8.0 | Positive - 497.8ft from Pit5 |
| 3e | Demo4 | Pit4 to Pit5 | 2.5 to 5.0 | Positive - 487.4ft from Pit5 |

Table 4: Demonstration Results

### Section 1: Pit#1 to Pit#2, Demonstration in Pit#4

The calibration test, Demo 1, was performed with a known flow rate of 0.6Gpm. The resulting correlation test presented a negative result. This suggests that a flow rate of 0.6Gpm or less cannot be detected with hydrophones at a sensor spacing of 1080.7ft or greater. Although the final result was negative this is still considered to be a successful calibration test as it has defined a range that cannot be successfully correlated.

The flow rates in Demo 2, 3, and 4 were unknown. Demo 2 presented a negative correlation test. This suggests that the flow rate is negligible and most likely to be close to or below the calibration value, 0.6Gpm. Demo 3 presented a positive result at a distance of 577.6ft from Pit #1. The character of the noise sources suggested a moderate sized flow rate in the range of 2.0 to 5.0Gpm. Demo 3 presented a positive result at a distance of 560.7ft from Pit #1. The coherence was very low and the correlation peak was weak suggesting that the flow rate was low. It is estimated that this flow rate is between 0 and 1.0Gpm but probably closer to 1.0Gpm as it is known that 0.6Gpm yielded a negative correlation.

### Section 2: Pit#2 to Pit#3, Demonstration in Pit #5

The calibration test, Demo 1, presented a negative result with no flow out of the test valves. This is as expected.  Demo 2 and Demo 3 presented very similar results. The correlated distances were within two feet of each other, 476.8ft and 478.8ft from Pit#3 respectively. Also, the character of the recordings was very similar suggesting that the flow rates are almost the same. It is estimated that the flow rates are both between 5.0 and 8.0Gpm but the similarity in the signals suggests that it may be flowing from the same orifice. Demo 4 presented a negative correlation result meaning that the flow rate is close to or below 0.6Gpm.

### Section 3: Pit#4 to Pit#5, Demonstration in Pit#2

The calibration test, Demo 1, was performed with a known flow rate of 8.0Gpm. The corresponding correlated distance was 502.9ft from Pit#5. The coherence was very strong and the correlation peak was prominent. Overall this test presented the loudest of all file recorded suggesting that it is the highest flow rate of all the demonstrations. Demo 2 presented a negative correlation result meaning that the flow rate is close to or below 0.6Gpm. Demo 3 presented a positive correlation result at a distance of 497.8ft from Pit#5. The recording had good coherence and a good correlation peak suggesting that there was a high flow rate. It is estimated that the flow rate for Demo 3 was between 5.0 and 8.0Gpm. Demo 4 presented a positive correlation result at a distance of 487.4ft from Pit#5. The coherence was lower than the previous test but the correlation peak was strong. It is estimated that the flow rate was between 2.5 and 5.0Gpm for Demo 4.

### General Comments

In some cases distance discrepancies between 2ft and 17ft is seen when the simulated leak is being generated in the same excavation pit. It is known that there is more than one valve in each of the demonstration pits but the distance between valves in the pit is unknown. It is assumed that the discrepancies are mainly due to the fact the valves are approximately 5ft apart, thus accounting for the difference. However, some of the difference may actually be due to signal processing error, which can get worse as the signal-to-noise ratio decreases. This may be the case for Demo 4, in Section 1: Pit#1 to Pit#2, Demonstration in Pit#4.

## 4.2. Leak Detection Results

There were two positive leak locations discovered over the duration of the testing.

### File #2a – Pit A to Pit B

File 2a was recorded with the Blue station on the pipe in Pit B and the White station in Pit A with sensor spacing of 260.5ft. The correlation function shown for this file indicates a leak at a position was 91.5ft from the White sensor. A sharp correlation peak and moderate levels of coherence indicates a flow rate of 2.5 – 5.0 Gpm for this leak.

The evidence presented here strongly indicates the presence of a leak and if this pipe were to remain in service, it would be suggested to perform remedial action.

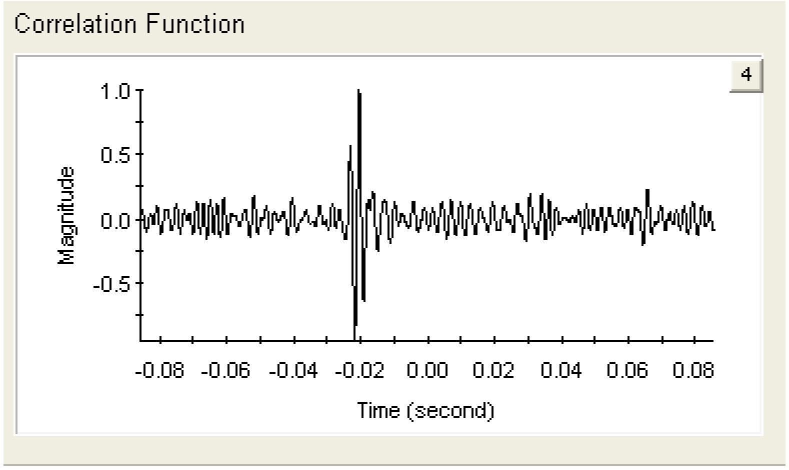


Figure 4: Correlation result for File #2

### File #7c – Pit F to Pit 3

The correlation function shown for File 7c was recorded with the Blue station mounted to the pipe in Pit F and the White station mounted to the pipe in Pit #3 with a sensor-to-sensor spacing of 312.7ft. The character of the signal suggests that there may be two leaks at this location at a distance of 126.6ft and 144.6ft from the White station. The weaker signal and wider correlation peak indicates a small leak, which sets the estimated flow rate at 1.0 – 2.5 Gpm for each leak.

The evidence presented here is not entirely conclusive because the correlation peak is not defined. If this pipe were to remain in service, it would be suggested to perform further investigation by either using a ground-microphone to confirm a noise source or potholing to confirm the presence of water.

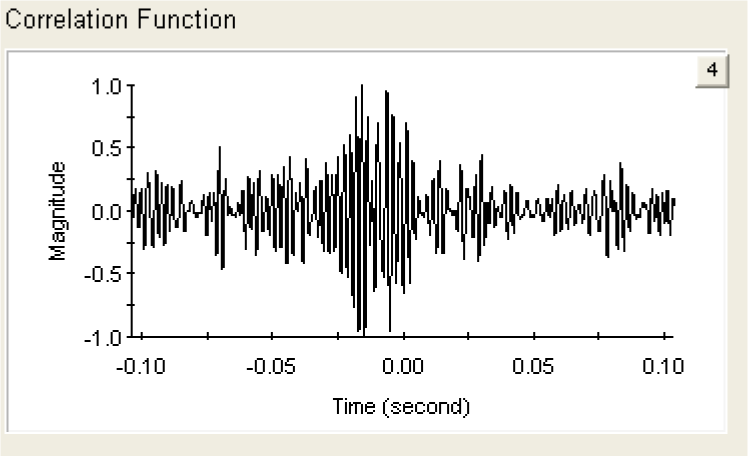


Figure 5: Correlation Result for File #7

## 4.3. Condition Assessment Results

The results of the condition assessment measurements are presented in Table 5: Condition Assessment Results. Starting from Pit #1, six sections in a row presented remaining equivalent thickness greater than 0.7-inches. This suggests that there may be some deterioration in these sections and the pipe is in good structural condition. The section showing the highest losses is between Pit F and Pit #3. It presented a remaining equivalent thickness of 0.69-inches.

It should be noted that the sections tested presented results approximately 14%-20% below the nominal values. This suggests that, overall; the pipe is still in good condition.

| File # | Location | Sensor-to-Sensor Spacing (ft) | Average Thickness (inch) | Condition |
|---|---|---|---|---|
| 1a | Pit1 to PitA | 250.7 | 0.73 | **Good** |
| 2c | PitA to PitB | 260.5 | 0.74 | **Good** |
| 3c | PitB to PitC | 298.6 | 0.75 | **Good** |
| 4b | PitC to Pit2 | 271 | 0.71 | **Good** |
| 5d | Pit2 to PitE | 360.9 | 0.71 | **Good** |
| 6c | PitE to PitF | 294.6 | 0.72 | **Good** |
| 7b | PitF to Pit3 | 312.7 | 0.69 | **Good** |

Table 5: Condition Assessment Results

## 5. Concluding Remarks

We thank you again for the opportunity to test the technology and we trust that this is acceptable. Please do not hesitate to contact us if there are any questions regarding the study.

Sincerely,

Echologics Engineering Inc.

M Bracken

______________________________

Marc Bracken, M.A.Sc., P.Eng.

Dave Johnston

______________________________

Dave Johnston, B.Eng. Materials Engineering

# 6. Appendix

Figure 6: Pipe Wall Cross-Section

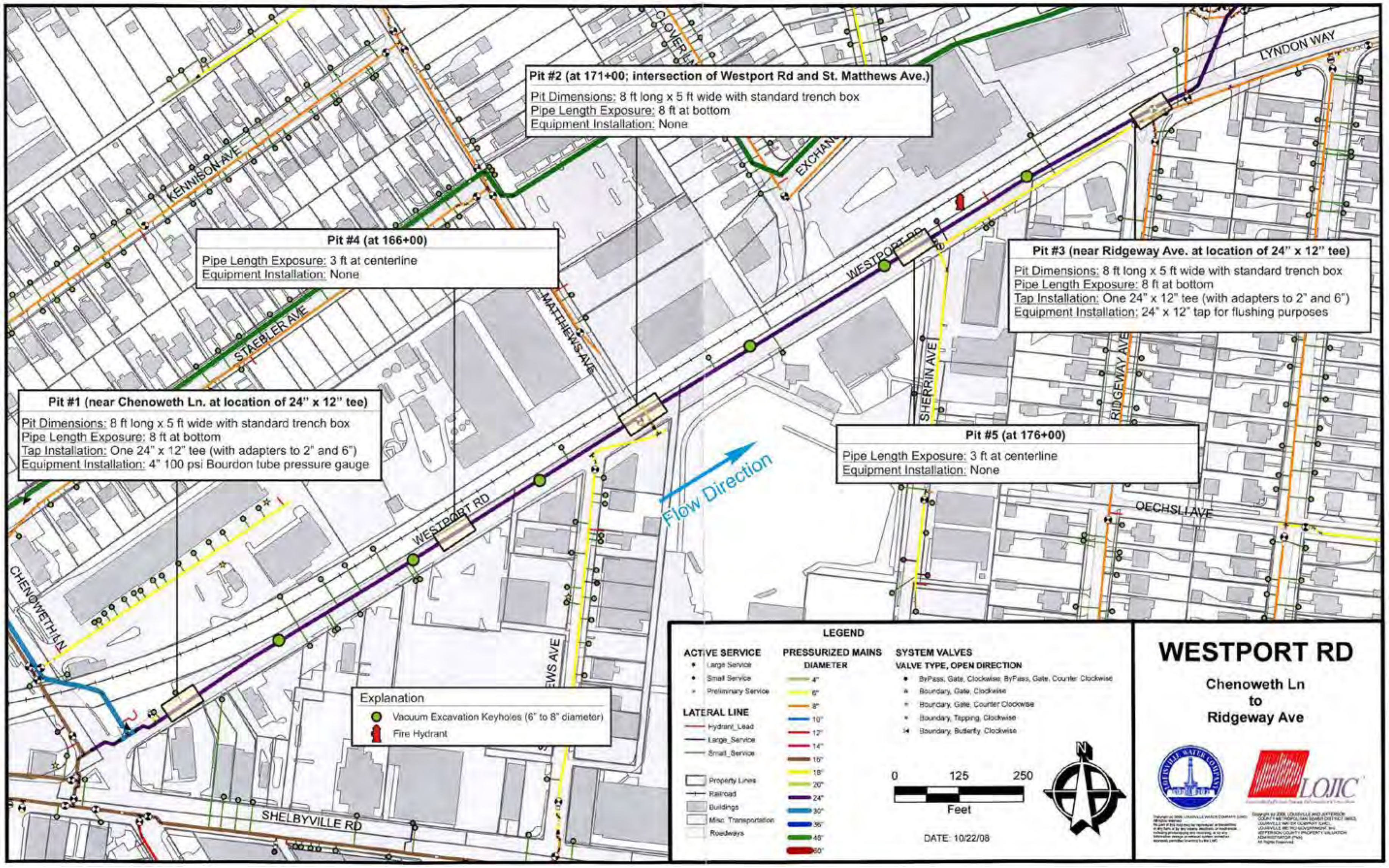
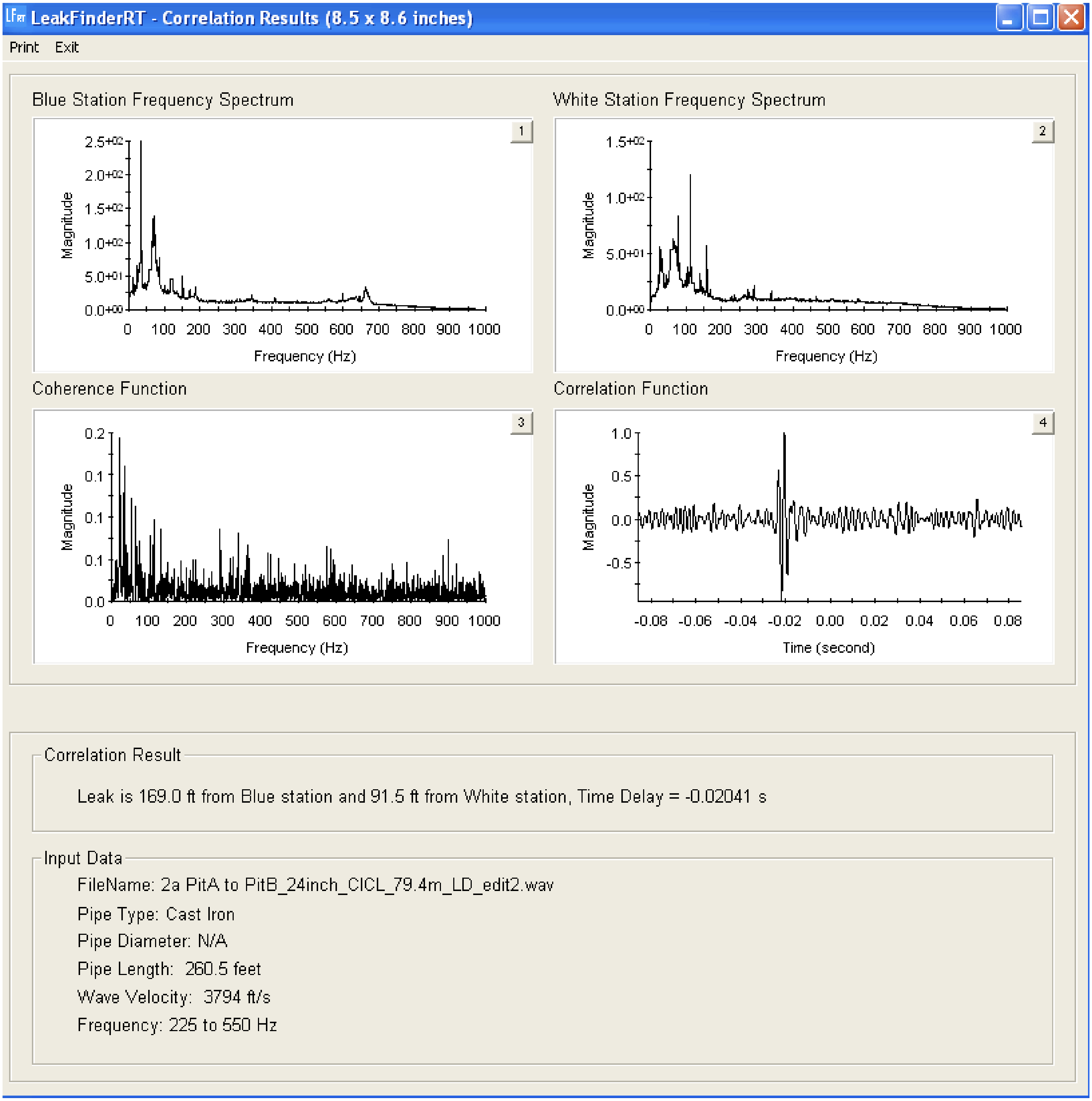


Figure 7: Site Layout



Correlation Result

Leak is 169.0 ft from Blue station and 91.5 ft from White station, Time Delay = -0.02041 s

Input Data

FileName: 2a PitA to PitB_24inch_CICL_79.4m_LD_edit2.wav

Pipe Type: Cast Iron

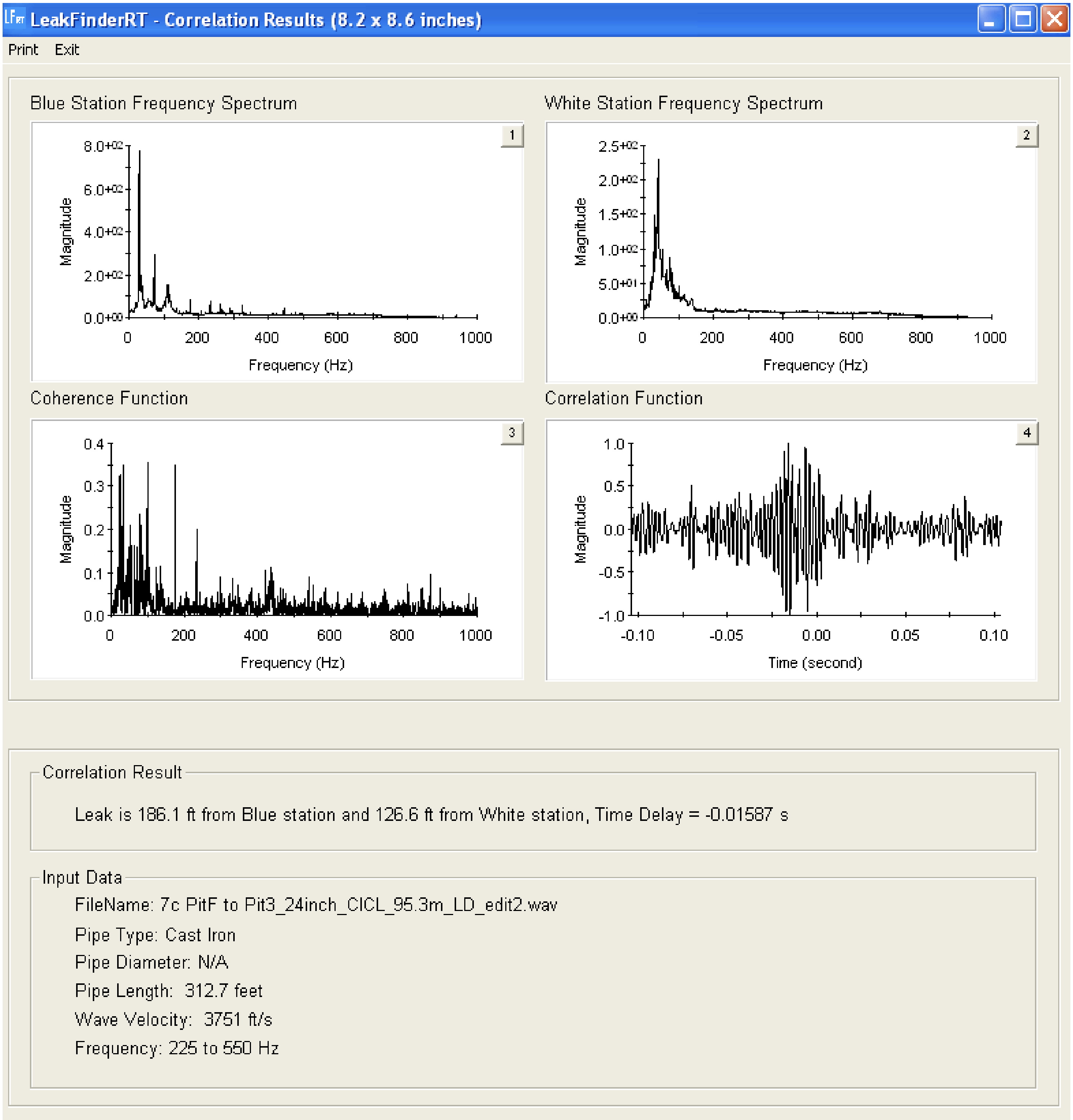
Pipe Diameter: N/A

Pipe Length: 260.5 feet

Wave Velocity: 3794 ft/s

Frequency: 225 to 550 Hz

Figure 8: Correlation Report for File #2a - PitA to PitB



Leak is 186.1 ft from Blue station and 126.6 ft from White station, Time Delay = -0.01587 s

FileName: 7c PitF to Pit3_24inch_CICL_95.3m_LD_edit2.wav
Pipe Type: Cast Iron
Pipe Diameter: N/A
Pipe Length: 312.7 feet
Wave Velocity: 3751 ft/s
Frequency: 225 to 550 Hz

**Figure 9: Correlation Report for File #7c - PitF to Pit3**

APPENDIX E

# RFT Inspection Condition Assessment (EPA Demo)

# Standard Analysis Report

## Russell NDE RFT ILI Tool for 24-inch Cast Iron Pipe

Westport Road
Between Shelbyville Road and Ridgeway Ave
Louisville, Kentucky, USA

Project: Battelle 06170901
PO: BMI #225941

| | |
|---|---|
| Inspection Date | September 4, 2009 |
| Analysts/Reviewers | YY, AS |
| Report Revision: | 0.2 |

# Table of Contents

# Louisville Westport Road Line

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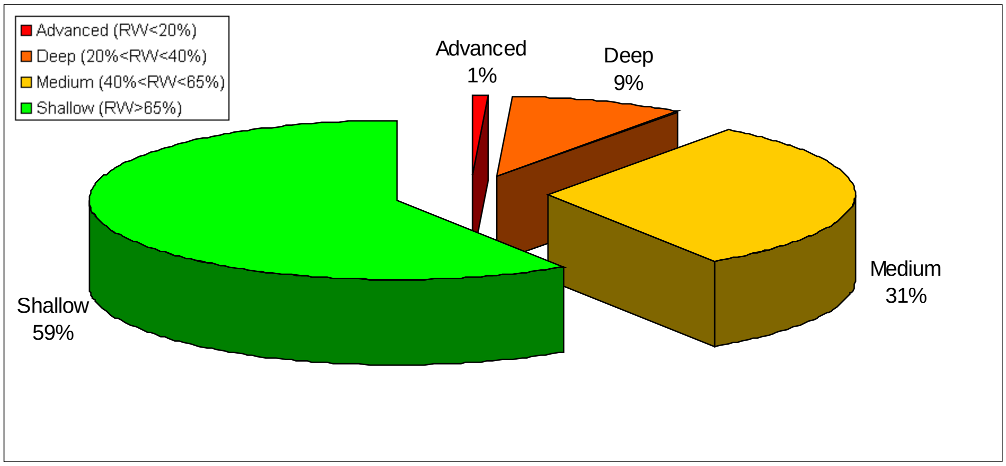
## 24-inch Cast Iron Water Main Assessment

### Executive Summary

Battelle Memorial Institute contracted Russell NDE Systems to inspect a 24-inch cast iron main along Westport Rd in Louisville, Kentucky, as part of a pipe assessment demonstration for the EPA. To perform the inspection, Russell NDE custom developed a 24-inch See Snake RFT tool. The inspection tool was completed at the end of August, 2009, and run through the line twice on September 3 and 4, 2009.

This report documents the RFT findings for the 24-inch Westport Rd main in Louisville. A total of 367 wall loss indications were found along the 2059ft main. A majority of these defects are less than or equal to 60% deep, with a much smaller group in the 60-80% range. Only a few localized indications sized 80% or deeper. In addition, the results from the 24-inch See Snake tool show that the deep defects are concentrated within the first half of the line, leaving about half the line in relatively good shape. The Pie chart and Table 1 provide a summary overview of the RFT findings and the measured remaining wall thickness.



- Figure 1. Defect break down according to minimum Local Remaining Wall.

| Feature Indication Summary: Louisville Westport Road Line | |
|---|---|
| Total number of Pipe sections | 170 |
| Total number of regular Bell-and-Spigot Joints | 168 |
| Total number of Coupling Joints | 0 |
| Number of Elbows | 0 |
| Number of Possible Tees, branches and Crosses | 2 |
| Number of Possible Valves | 2 |
| Number of joints with different material properties (different nominal WT) | 0 |
| Number of Joints without Wall Loss Indications | 24 |
| Number of Joints with Wall Loss Indications | 146 |
| Total Number of Wall Loss Indications | 367 |
| Number of Joints with noise or other anomalies | 8 |

- Table 1. Feature Indication Summary for Louisville WestPort Road line,

# Pipeline Inspection Background

## Pipeline Information ("the what and where")

| | | |
|---|---|---|
| **Client:** | Battelle Memorial Institute / EPA | |
| | | |
| **Location:** | Westport Road<br>Between Shelbyville Road and Ridgeway Ave<br>Louisville, Kentucky, USA | |
| | See Appendix 2 for satellite image | |
| | | |
| **Pipe Size:** | 24-inch | |
| **Year Installed:** | 1933 | |
| **Nominal WT:** | 0.75" (19.1mm) | |
| **Material:** | Cast Iron | |
| **Access:** | West most excavation ("launch pit") | |
| **Internal Liner:** | Concrete | 0.25-inch Thickness |
| **External:** | | |
| **Bends:** | None | |
| **CP:** | None | |
| **Features:** | Small service connections and possible hydrant branches | |
| **Length:** | 2059[ft] | |

- Table 2. Pipeline Information for Louisville Westport Road Line

## Operation

In preparation for the See Snake inspection, Battelle and MAC Construction fed a mule tape through the 24-inch force main. The mule tape was used to pull a steel wireline through line, with the wireline winch setup at the West excavation and a tagline winch setup at the East excavation. The inspection tool was attached to both winches allowing it to be pulled in both directions.

The See Snake tool is self contained and does not require to be powered through a wireline. It can handle pipe diameters in the range of 21 to 27-inches and has an overall length of 97-inches. The figure below shows the tool in preparation for launch.

- Figure 2. See Snake smart pig being lowered onto tray in excavation provided by Mac Construction in preparation of launch.

Traveled distance was measured by running the west-side tether over an odometer wheel. The wheel was mounted on a hydrant adapter, which in turn was positioned above ground in between the winch truck and the excavation.

## Inspection

The tool was placed in the west excavation (exciter end first) and positioned with the detectors just outside of the pipe prior to the pull beginning, making the edge of the pipe the datum point for the RFT log. All footages found in the report are offset by 8ft from this datum point and are referenced to the above ground zero-foot marker used by Battelle.

- Figure 3. Tool start position with hydrant adaptor and odometer wheel.

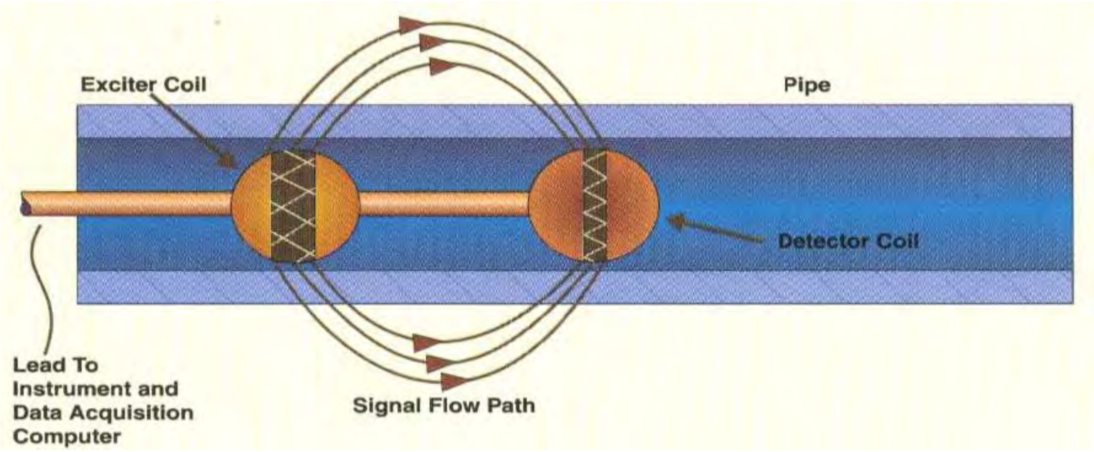
To prevent rubbing of the cable against the inside of the pipe opening, a roller system at the pipe entrance was improvised in the field.

Two runs were performed; with the first one on September 3. Upon download and review of the September 3rd data, the inspection speed was too determined too high, and the tool appeared to have experienced significant surging during the inspection. As a result, it was decided to rerun the line the next day at a lower speed.

On September 4th, the tagline winch at the east excavation began pulling the tool into the line shortly after 8:30am at a target speed of 15 feet/min. The inspection took approximately 2.5 hours to complete. The tool was disassembled in the East pit, and retrieved using the backhoe.

**See Snake tool description**

The Russell NDE Systems' See Snake line of RFT tools are pipe inspection tools that employ Remote Field Technology for measuring pipe wall thickness. RFT technology works by detecting changes in an AC electromagnetic field generated by the tool. The field interacts with the metal in the encompassing pipe and becomes stronger in areas of metal loss. The field interactions are measured by on board detectors, and subsequently processed on the tool itself using A/D converters and digital processors. The processed data is stored on board. Once all the data is acquired, dedicated analysis software is applied to generate accurate information on the wall thickness of the line. Figure 4 below schematically shows the magnetic coupling path between the exciter section of the tool and the detectors.



- Figure 4. Schematic of magnetic interaction between RFT tool and Pipe

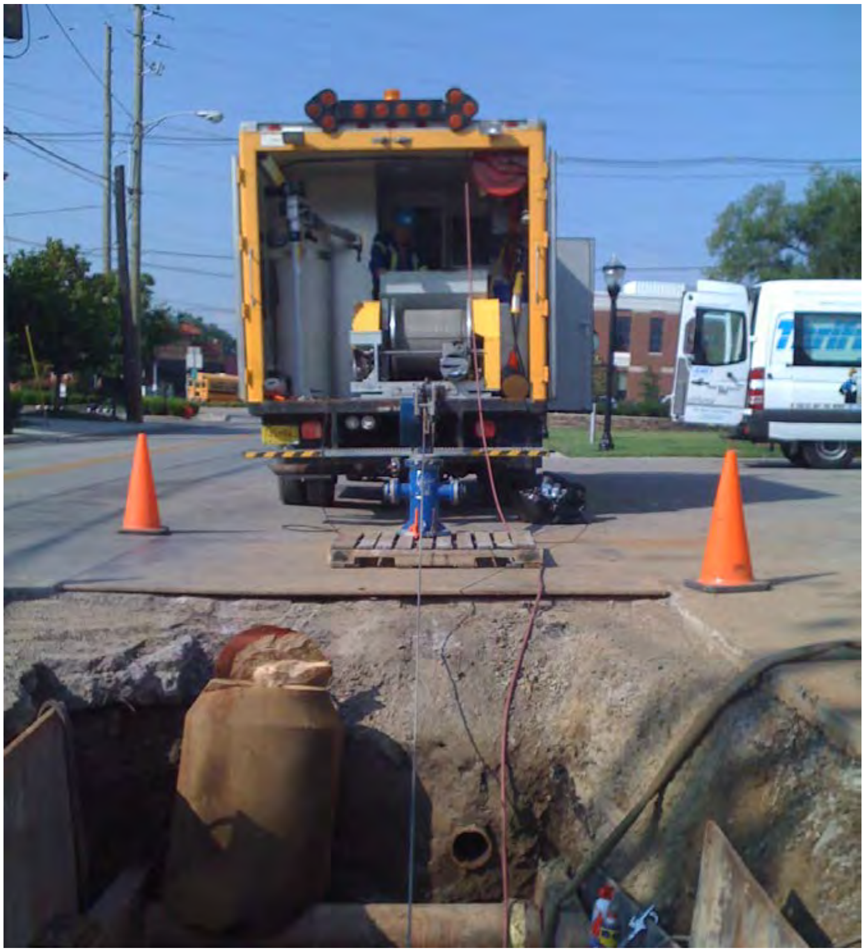
The hard diameter of the tool is significantly smaller than the ID of the pipe to allow for protrusions, lining and scale. Centralizers maintain a uniform annulus between the tool and the pipe. The connection with the street-level world is made through a wire line, which runs over an odometer sheave to provide an accurate distance reading of the tool.

The tool detects wall thinning caused by corrosion or erosion, as well as line features such as joint couplings, branches and elbows. The range is limited by battery power for free swimming runs, and the amount of wire-line on the winch for tethered runs.

The complete system used to perform the waterline inspection includes the following equipment:

- 24-inch Waterline See Snake RFT tool with data download USB box.
- Odometer Hydrant Adapter, with supporting shoring rod.
- Cleaning Swab
- Wireline truck with winch fitted with 1km of wireline.
- Odometer Adaptor Box
- Laptop running Distance Logger (1.2.3).
- Following data download and viewing software: Linx version 1.9.7, Merger Version 1.7.16, AdeptPro MC 1.5.

The image below shows the setup, with winch truck, hydrant odometer, shoring rod, and spent cleaning swab. The wireline truck is aligned with the launch point to insure the straightest pull possible from the winch to the entry point.

- 

- Figure 5. Wireline Truck and hydrant setup during EPA demo September 2009.

## Field Notes

| | | | | | |
|---|---|---|---|---|---|
| **Examination Date:** | 04 Sep.09 | **Arrive Site:** | 07:00 | **Depart Site:** | 14:30 |
| **Lead Technician:** | DER | | **Technician** | DCL, YMY, AS | |
| **Weather:** | Hot (100°F). Clear. Humid | | | | |
| **Target Distance:** | 2100ft m | **Examined Distance:** | 2059ft | **Run Direction:** | West to East |
| **Launch:** | West most excavation pit | **GIS Ref:** | | | |
| **Field Sketch & Site Observations:** | | Appendix 2 | | | |
| **Swabbing Performed By:** | Louisville Water Company and Russell NDE | | | | |
| **No. Soft Swabs:** | 1 | | **No. Hard Swabs:** | | 0 |
| **Operational Comments:** | | | | | |
| Run was performed twice, because of surging and high speeds during first inspection on Sep 3, 2009. | | | | | |
| | | | | | |
| | | | | | |

- Table 3. Inspection notes from Field Crew.

# Calibration

Battelle prepared wall loss defects of different depths and size at selected locations along the length of the pipe. The specifications of a number of these defects were shared with Russell NDE Systems to allow calibration of the RFT equipment.

Unfortunately, the RFT data at the specified locations for the calibration defects was extremely noisy. The noise was present on both the September 3rd data and the September 4th data, pointing at possible magnetic permeability noise.

In general the magnetic permeability of a pipe section remains fairly constant over its length; however it is possible for stresses or other external factors to locally change the permeability of the steel material. This is quite unusual, but if present, the RFT tool (which measures magnetic fields far weaker than the earth's magnetic field) would see these changes in the magnetic properties of the pipe. If the magnetic permeability variations are very strong, they can become "noise" that masks potential defects.

Possible causes for the permeability noise:

1) If the calibration defects were machined with no or little coolant, this could cause stresses in the pipe around the defects and locally change the magnetic permeability.
2) If the machining equipment for the defects employed a magnetic base to clamp the equipment to the pipe, the strong permanent magnets would alter the permeability significantly.
3) It is also possible that some of the other NDE techniques used permanent magnets for attaching their external scanning devices, again these would leave large magnetic "imprints".
4) Finally, some of the other NDE techniques may have tried to magnetically saturate the pipes at the defect locations. That process would also leave large magnetic imprints on the pipe.

For optimal RFT accuracy, a calibration is performed using pipe with the same nominal pipe properties (WT and grade) as the pipe being inspected. However, in this case the data from the calibration defects was too noisy to be usable. So instead the calibration was performed by running the tool through a 24-inch calibration pipe in our yard and comparing the data from the cast-iron main to data from the yard calibration.

Based on the above procedure, the defect accuracy is expected to be +20%/-20% for short (local) wall loss, and +/-10% for long (general) wall loss. The above accuracy range is valid for indications sufficiently removed from major features, such as Bell-and-Spigot connections.

# Analysis Results

### Location Reporting and Inspection Lengths.

The logged distance data for the Louisville Westport Road Line was 2059ft, with zero set at the launch hydrant Tee. The first three joints were not analyzed due to initial surging at the start, and because the joints were the first to be removed as part of the replacement program.

### Analysis Results

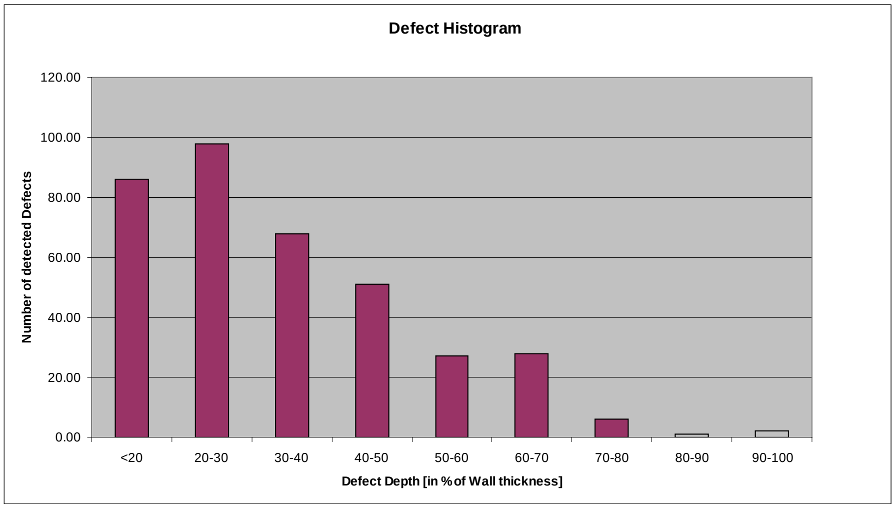
Features

All Bell-and-Spigot joints were clearly visible in the data. Some other large features were observed, but they could not always be correlated back to above ground observations from the field crew. Valves and tees branches are indicated were believed present.

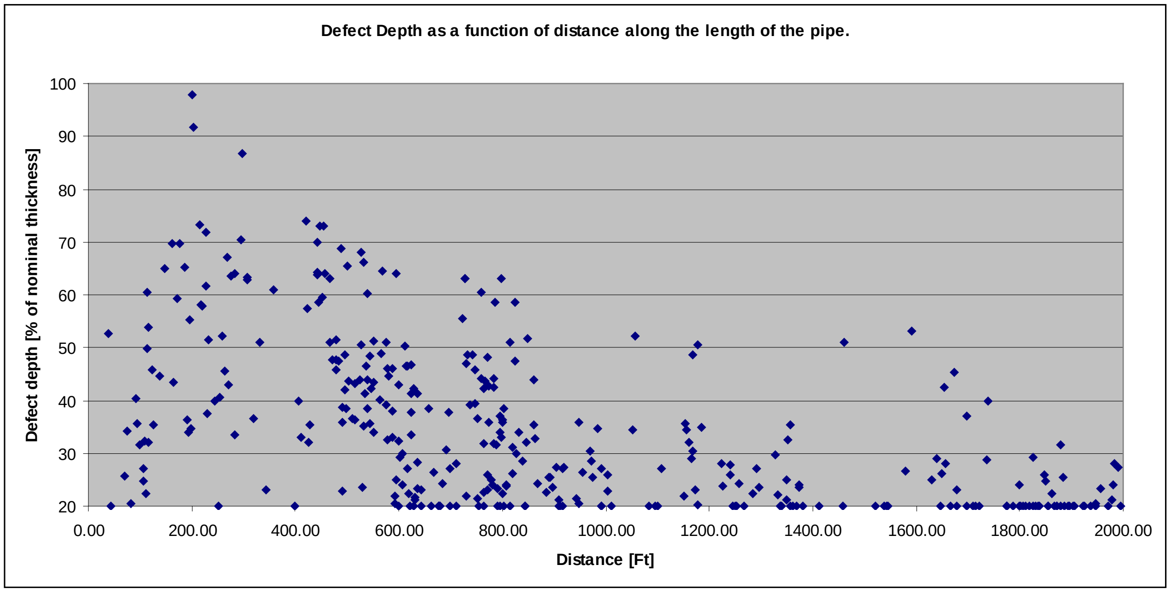
- 12.2ft joint lengths were common throughout the line. For a detailed joint breakdown please see the Pipe Tally table in Appendix 1, which provides locations of the Bell-and-Spigot.
- A number of major line features were noticed in the data. These are believed to be two valves and two branches.

Anomalies

The inspection of the water line resulted in 367 wall loss indications. A histogram of the results show that a majority of the defects are less than or equal to 50% deep, with a much smaller group in the 60-80% range, and only a few defects 90% or deeper. More importantly the results from the See Snake tool show that the deep defects are concentrated within the first half of the line, leaving about half the line in relatively good shape.



- Figure 6. Defect Histogram (for example the count at 70% deep are defects that are deeper than 60% but less than 70%).



- Figure 7. Defect Scatter graph

See appendix 1 for a complete list of recorded wall loss anomalies. Both location and clock position are documented.

# Disclaimer

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### SCOPE OF SERVICES:

The agreement of Russell NDE Systems Inc. to perform services extends only to those services provided for in writing. Under no circumstances shall such services extend beyond the performance of the requested services. It is expressly understood that all descriptions, comments and expressions of opinion reflect the opinions or observations of Russell NDE Systems Inc. based on information and assumptions supplied by the owner/operator and are not intended nor can they be construed as representations or warranties. Russell NDE Systems Inc. is not assuming any responsibilities of the owner/operator and the owner/operator retains complete responsibility for the engineering, manufacture, repair and use decisions as a result of the data or other information provided by Russell NDE Systems Inc. Nothing contained in this Agreement shall create a contractual relationship with or cause of action in favor of a third party against either the Line Owner or Russell NDE Systems Inc. In no event shall Russell NDE Systems Inc.’s liability in respect of the services referred to herein exceed the amount paid for such services.

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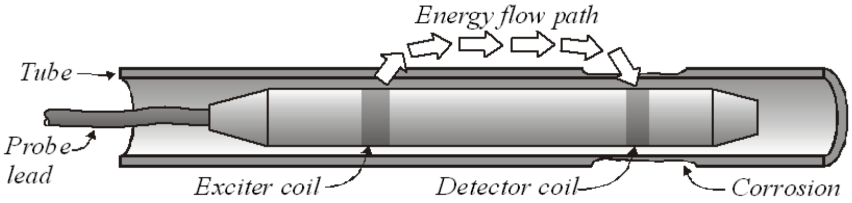
# Compilation of Background Information for Report

Russell NDE Systems Inc undertakes to take every reasonable effort to generate an accurate “Condition Assessment Analysis” upon completion of the “Data Acquisition Stage” of each “Infrastructure Condition Assessment Contract”. This often requires fact checking against sources of information from the client as well as third party contractors and vendors. Such information falls into the categories of Properties of the Pipe; (Material & Physical properties), Pipe Fittings; (Dimensional and Positional information), Pipeline Design; (Plan & Profile Drawings – sub-surface piping, ISO Drawings of surface infrastructure), Construction Methods for the Pipeline; (Shop Bends vs. Field Bends), Protection Infrastructure for the Pipeline; (Active or Passive Cathodic Protection, Rock Guard exterior coating, interior lining, casings, etc.), Alterations to the Pipeline; (Repairs, Changes, Additions), Corrosion/Erosion Information for the Pipeline; (Break History, Independent NDT Inspection of Dig Sites, Laboratory Analysis of Corrosion Deposits) Ancillary Services used to complete the ILI Data Acquisition; (Nitrogen, Compressed Air, Water Pumping to propel the ILI to Target distance) and any other related factors that may aid in obtaining the most accurate report results currently available.

### Background information on tool.

In the basic RFT probe shown in the figure below, there is one exciter coil and one detector coil. Both coils are wound co-axial with respect to the examined pipe, and are separated by a distance greater than two (2) times the pipe diameter. The actual separation depends on the application, but will always be a minimum of 2 pipe diameters. It is this separation that gives RFT its name - the detector measures the EM field remote from the exciter. Although the fields have become very small at this distance from the exciter, they contain information on the full thickness of the pipe wall.



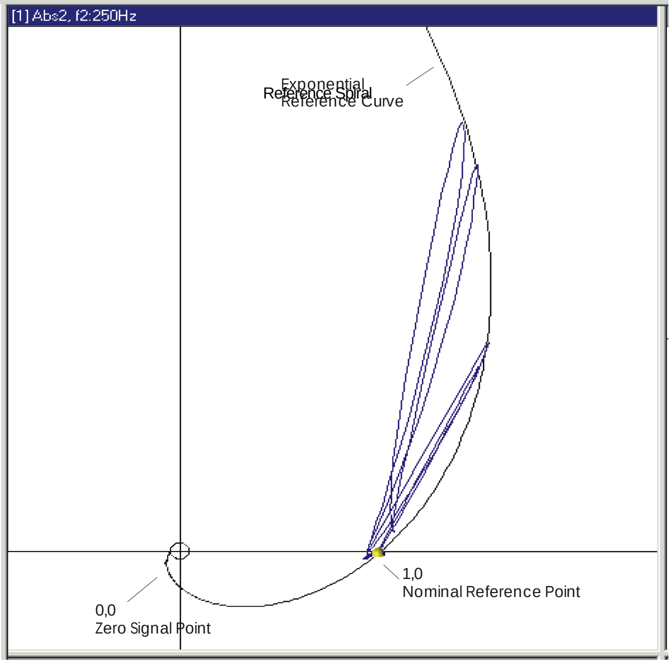
The detector electronics include high-gain instrumentation amplifiers and steep noise filters. These are necessary in order to retrieve the remote field signals. The detector electronics output the amplitude and phase of the remote field signal to an on-board storage device. The data is recalled for display, analysis and reporting purposes after the examination process is completed.

### Presenting RFT data: Strip Chart display & Phase-Amplitude Diagrams.

A Strip Chart displays the detector data as a function of time or the axial distance along the length of the pipeline. Phase and log-amplitude are the preferred quantities for the strip-chart display, because they are both linear indicators of overall wall-thickness. The general convention for strip charts is that deflections to the left represent metal loss, and deflections to the right wall thickening.

A phase-amplitude diagram is a two-dimensional representation of the detector output voltage, with the angle representing phase with respect to a reference signal, and the radius representing amplitude (ASNT E 2096). The detector signals are drawn as vector points in polar coordinates with the angle representing the phase and the radius representing the amplitude. Axial distance information is not available on amplitude-phase diagrams; yet, they are used for sizing flaws. By combining amplitude-phase diagrams with strip charts, the distance information can be included.

Phase amplitude diagrams are also known as "voltage plane displays". On the voltage plane display, the nominal signal is placed at (1,0). Besides the detector information, the Voltage Plane has a number of static components: the origin, the x- and y-axes, and the exponential skin depth reference curve. The curve starts at 0,0 (i.e. zero voltage, at origin), and follows a spiral path that traces the path (locus) of the phasors as the overall wall thickness of a casing is decreased. Full circumferential flaws fall directly on this curve (see figure on the right for examples of full circumferential defect indications).



# Appendix 2: Site Sketch

• Louisville Westport Road Line Site Sketch.

## Appendix 3: RFT Inspection results for the 24-inch cast iron pipe Westport Rd demo

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 8.00 | | | | | | | | | Start of run |
| 12.50 | | 1 | | | | | | | B/S |
| 24.50 | | 2 | | | | | | | B/S |
| 36.55 | | 3 | | | | | 66 | | B/S |
| 38.99 | 2.44 | | 0.75 | 53 | 47 | 0.35 | 333 | 4:00 | Wall Loss Indication |
| 44.05 | 7.50 | | 0.75 | <20 | >80 | >0.6 | 889 | 4:30 | Wall Loss Indication |
| 48.74 | | 4 | | | | | 1404 | | B/S |
| 60.94 | | 5 | | | | | 2871 | | B/S |
| 70.77 | 9.83 | | 0.75 | 26 | 74 | 0.56 | 4054 | 8:30 | Wall Loss Indication |
| 73.16 | | 6 | | | | | 4341 | | B/S |
| 74.94 | 1.78 | | 0.75 | 34 | 66 | 0.49 | 4555 | 5:30 | Wall Loss Indication |
| 81.74 | 8.58 | | 0.75 | 21 | 79 | 0.60 | 5373 | 11:00 | Wall Loss Indication |
| 85.41 | | 7 | | | | | 5814 | | B/S |
| 92.41 | 7.00 | | 0.75 | 40 | 60 | 0.45 | 6656 | 11:00 | Wall Loss Indication |
| 94.29 | 8.88 | | 0.75 | 36 | 64 | 0.48 | 6882 | 11:00 | Wall Loss Indication |
| 97.54 | | 8 | | | | | 7273 | | B/S |
| 99.40 | 1.87 | | 0.75 | 32 | 68 | 0.51 | 7498 | 4:30 | Wall Loss Indication |
| 105.94 | 8.40 | | 0.75 | 27 | 73 | 0.55 | 8284 | 9:00 | Wall Loss Indication |
| 106.96 | 9.42 | | 0.75 | 25 | 75 | 0.56 | 8406 | 11:00 | Wall Loss Indication |
| 108.53 | 11.00 | | 0.75 | 32 | 68 | 0.51 | 8596 | 8:30 | Wall Loss Indication |
| 109.73 | | 9 | | | | | 8739 | | B/S |
| 111.30 | 1.57 | | 0.75 | 22 | 78 | 0.58 | 8928 | 4:30 | Wall Loss Indication |
| 112.59 | 2.86 | | 0.75 | 50 | 50 | 0.38 | 9084 | 4:30 | Wall Loss Indication |
| 114.62 | 4.89 | | 0.75 | 60 | 40 | 0.30 | 9328 | 5:00 | Wall Loss Indication - Major |
| 115.67 | 5.94 | | 0.75 | 32 | 68 | 0.51 | 9454 | 5:00 | Wall Loss Indication - Major |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 117.10 | 7.37 | | 0.75 | 54 | 46 | 0.35 | 9626 | 4:30 | Wall Loss Indication - Major |
| 121.90 | | 10 | | | | | 10203 | | B/S |
| 123.96 | 2.06 | | 0.75 | 46 | 54 | 0.41 | 10451 | 12:00 | Wall Loss Indication |
| 125.29 | 3.38 | | 0.75 | 35 | 65 | 0.49 | 10610 | 12:00 | Wall Loss Indication |
| 134.12 | | 11 | | | | | 11672 | | B/S |
| 137.57 | 3.45 | | 0.75 | 45 | 55 | 0.42 | 12087 | 4:30 | Wall Loss Indication |
| 146.33 | | 12 | | | | | 13141 | | B/S |
| 148.67 | 2.34 | | 0.75 | 65 | 35 | 0.26 | 13423 | 11:00 | Wall Loss Indication - Major |
| 158.42 | | 13 | | | | | 14595 | | B/S |
| 161.20 | 2.78 | | 0.75 | 70 | 30 | 0.23 | 14930 | 4:30 | Wall Loss Indication - Major |
| 165.48 | 7.06 | | 0.75 | 44 | 56 | 0.42 | 15445 | 9:30 | Wall Loss Indication |
| 170.63 | | 14 | | | | | 16064 | | B/S |
| 172.18 | 1.55 | | 0.75 | 59 | 41 | 0.30 | 16250 | 4:30 | Wall Loss Indication |
| 177.42 | 6.78 | | 0.75 | 70 | 30 | 0.23 | 16880 | 4:30 | Wall Loss Indication |
| 182.83 | | 15 | | | | | 17531 | | B/S |
| 185.11 | 2.28 | | 0.75 | 65 | 35 | 0.26 | 17805 | 4:30 | Wall Loss Indication |
| 191.75 | 8.92 | | 0.75 | 36 | 64 | 0.48 | 18604 | 10:30 | Wall Loss Indication |
| 192.53 | 9.71 | | 0.75 | 34 | 66 | 0.49 | 18698 | 8:30 | Wall Loss Indication |
| 195.17 | | 16 | | | | | 19015 | | B/S |
| 197.06 | 1.90 | | 0.75 | 55 | 45 | 0.34 | 19243 | 3:30 | Wall Loss Indication |
| 198.53 | 3.36 | | 0.75 | 35 | 65 | 0.49 | 19420 | 8:30 | Wall Loss Indication |
| 199.91 | 4.74 | | 0.75 | 98 | 2 | 0.02 | 19585 | 4:30 | Wall Loss Indication |
| 202.52 | 7.35 | | 0.75 | 92 | 8 | 0.06 | 19900 | 4:30 | Wall Loss Indication |
| 207.46 | | 17 | | | | | 20494 | | B/S |
| 215.37 | 7.91 | | 0.75 | 73 | 27 | 0.20 | 21445 | 4:00 | Wall Loss Indication |
| 216.87 | 9.41 | | 0.75 | 58 | 42 | 0.31 | 21625 | 9:30 | Wall Loss Indication |
| 219.48 | | 18 | | | | | 21939 | | B/S |
| 220.78 | 1.30 | | 0.75 | 58 | 42 | 0.32 | 22096 | 4:00 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 226.62 | 7.13 | | 0.75 | 72 | 28 | 0.21 | 22798 | 4:30 | Wall Loss Indication |
| 227.35 | 7.86 | | 0.75 | 62 | 38 | 0.29 | 22885 | 9:30 | Wall Loss Indication |
| 229.39 | 9.91 | | 0.75 | 37 | 63 | 0.47 | 23131 | 10:30 | Wall Loss Indication |
| 231.63 | | 19 | | | | | 23400 | | B/S |
| 233.00 | 1.38 | | 0.75 | 52 | 48 | 0.36 | 23565 | 10:30 | Wall Loss Indication |
| 243.74 | | 20 | | | | | 24857 | | B/S |
| 244.98 | 1.24 | | 0.75 | 40 | 60 | 0.45 | 25005 | 3:30 | Wall Loss Indication |
| 251.24 | 7.50 | | 0.75 | <20 | >80 | >0.6 | 25759 | 10:30 | Wall Loss Indication |
| 253.11 | 9.37 | | 0.75 | 41 | 59 | 0.45 | 25983 | 4:00 | Wall Loss Indication |
| 255.90 | | 21 | | | | | 26319 | | B/S |
| 259.17 | 3.27 | | 0.75 | 52 | 48 | 0.36 | 26713 | 3:00 | Wall Loss Indication |
| 262.94 | 7.04 | | 0.75 | 46 | 54 | 0.41 | 27167 | 11:00 | Wall Loss Indication |
| 268.01 | | 22 | | | | | 27776 | | B/S |
| 269.27 | 1.26 | | 0.75 | 67 | 33 | 0.25 | 27927 | 4:00 | Wall Loss Indication |
| 270.44 | 2.42 | | 0.75 | 43 | 57 | 0.43 | 28068 | 3:30 | Wall Loss Indication |
| 275.44 | 7.42 | | 0.75 | 64 | 36 | 0.27 | 28669 | 3:30 | Wall Loss Indication |
| 280.25 | | 23 | | | | | 29247 | | B/S |
| 281.93 | 1.69 | | 0.75 | 34 | 66 | 0.50 | 29450 | 10:30 | Wall Loss Indication |
| 283.22 | 2.97 | | 0.75 | 64 | 36 | 0.27 | 29605 | 4:00 | Wall Loss Indication |
| 292.63 | | 24 | | | | | 30737 | | B/S |
| 294.91 | 2.29 | | 0.75 | 70 | 30 | 0.22 | 31003 | 4:00 | Wall Loss Indication - Major |
| 297.96 | 5.33 | | 0.75 | 87 | 13 | 0.10 | 31358 | 4:00 | Wall Loss Indication - Major |
| 304.82 | | 25 | | | | | 32157 | | B/S |
| 306.34 | 1.53 | | 0.75 | 63 | 37 | 0.28 | 32341 | 4:00 | Wall Loss Indication - Major |
| 307.16 | 2.34 | | 0.75 | 63 | 37 | 0.28 | 32440 | 3:30 | Wall Loss Indication - Major |
| 316.96 | | 26 | | | | | 33619 | | B/S |
| 319.57 | 2.61 | | 0.75 | 36 | 64 | 0.48 | 33971 | 4:00 | Wall Loss Indication |
| 328.97 | | 27 | | | | | 35238 | | B/S |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 332.31 | 3.35 | | 0.75 | 51 | 49 | 0.37 | 35642 | 10:00 | Wall Loss Indication |
| 341.45 | | 28 | | | | | 36742 | | B/S |
| 344.04 | 2.59 | | 0.75 | 23 | 77 | 0.58 | 37009 | 3:30 | Wall Loss Indication |
| 353.64 | | 29 | | | | | 38003 | | B/S |
| 356.81 | 3.17 | | 0.75 | 61 | 39 | 0.29 | 38358 | 3:00 | Wall Loss Indication |
| 365.83 | | 30 | | | | | 39370 | | B/S |
| 378.05 | | 31 | | | | | 40840 | | B/S |
| 390.32 | | 32 | | | | | 42316 | | B/S |
| 398.28 | 7.95 | | 0.75 | <20 | >80 | >0.6 | 43272 | 5:00 | Wall Loss Indication |
| 402.50 | | 33 | | | | | 43779 | | B/S |
| 406.06 | 3.56 | | 0.75 | 40 | 60 | 0.45 | 44208 | 3:00 | Wall Loss Indication |
| 411.03 | 8.53 | | 0.75 | 33 | 67 | 0.50 | 44806 | 9:00 | Wall Loss Indication |
| 414.77 | | 34 | | | | | 45255 | | B/S |
| 419.82 | 5.05 | | 0.75 | 74 | 26 | 0.20 | 45863 | 3:00 | Wall Loss Indication |
| 422.74 | 7.97 | | 0.75 | 57 | 43 | 0.32 | 46214 | 2:30 | Wall Loss Indication |
| 425.00 | 10.23 | | 0.75 | 32 | 68 | 0.51 | 46486 | 9:00 | Wall Loss Indication |
| 426.95 | | 35 | | | | | 46721 | | B/S |
| 429.01 | 2.06 | | 0.75 | 35 | 65 | 0.49 | 46968 | 3:00 | Wall Loss Indication |
| 439.16 | | 36 | | | | | 48190 | | B/S |
| 441.97 | 2.80 | | 0.75 | 64 | 36 | 0.27 | 48527 | 2:30 | Wall Loss Indication |
| 442.61 | 3.44 | | 0.75 | 70 | 30 | 0.23 | 48604 | 2:30 | Wall Loss Indication |
| 443.63 | 4.47 | | 0.75 | 64 | 36 | 0.27 | 48727 | 3:00 | Wall Loss Indication |
| 445.86 | 6.69 | | 0.75 | 59 | 41 | 0.31 | 48995 | 2:30 | Wall Loss Indication |
| 447.78 | 8.62 | | 0.75 | 73 | 27 | 0.20 | 49226 | 2:30 | Wall Loss Indication |
| 451.29 | | 37 | | | | | 49647 | | B/S |
| 452.83 | 1.55 | | 0.75 | 60 | 40 | 0.30 | 49834 | 2:30 | Wall Loss Indication |
| 455.47 | 4.18 | | 0.75 | 73 | 27 | 0.20 | 50150 | 2:30 | Wall Loss Indication |
| 457.52 | 6.24 | | 0.75 | 64 | 36 | 0.27 | 50397 | 2:30 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 463.48 | | 38 | | | | | 51114 | | B/S |
| 465.90 | 2.42 | | 0.75 | 63 | 37 | 0.28 | 51406 | 2:00 | Wall Loss Indication |
| 467.25 | 3.77 | | 0.75 | 51 | 49 | 0.37 | 51568 | 9:30 | Wall Loss Indication |
| 470.56 | 7.08 | | 0.75 | 48 | 52 | 0.39 | 51966 | 2:30 | Wall Loss Indication |
| 475.70 | | 39 | | | | | 52584 | | B/S |
| 478.21 | 2.50 | | 0.75 | 52 | 48 | 0.36 | 52885 | 2:30 | Wall Loss Indication |
| 478.37 | 2.66 | | 0.75 | 48 | 52 | 0.39 | 52904 | 9:00 | Wall Loss Indication |
| 479.77 | 4.07 | | 0.75 | 46 | 54 | 0.41 | 53074 | 2:30 | Wall Loss Indication |
| 482.64 | 6.93 | | 0.75 | 48 | 53 | 0.39 | 53418 | 9:00 | Wall Loss Indication |
| 487.86 | | 40 | | | | | 54047 | | B/S |
| 488.61 | 0.75 | | 0.75 | 69 | 31 | 0.23 | 54137 | 9:00 | Wall Loss Indication |
| 489.95 | 2.09 | | 0.75 | 39 | 61 | 0.46 | 54298 | 10:30 | Wall Loss Indication |
| 490.16 | 2.29 | | 0.75 | 23 | 77 | 0.58 | 54323 | 9:30 | Wall Loss Indication |
| 491.85 | 3.98 | | 0.75 | 36 | 64 | 0.48 | 54525 | 6:30 | Wall Loss Indication |
| 494.84 | 6.97 | | 0.75 | 42 | 58 | 0.43 | 54885 | 6:30 | Wall Loss Indication |
| 496.60 | 8.74 | | 0.75 | 49 | 51 | 0.38 | 55098 | 8:30 | Wall Loss Indication |
| 498.44 | 10.58 | | 0.75 | 38 | 62 | 0.46 | 55319 | 9:00 | Wall Loss Indication |
| 500.08 | | 41 | | | | | 55515 | | B/S |
| 500.62 | 0.54 | | 0.75 | 66 | 34 | 0.26 | 55580 | 2:30 | Wall Loss Indication |
| 502.06 | 1.99 | | 0.75 | 44 | 56 | 0.42 | 55754 | 1:30 | Wall Loss Indication |
| 509.83 | 9.76 | | 0.75 | 37 | 63 | 0.47 | 56689 | 9:00 | Wall Loss Indication |
| 512.31 | | 42 | | | | | 56987 | | B/S |
| 514.25 | 1.95 | | 0.75 | 43 | 57 | 0.43 | 57221 | 2:30 | Wall Loss Indication |
| 515.05 | 2.74 | | 0.75 | 36 | 64 | 0.48 | 57317 | 2:30 | Wall Loss Indication |
| 524.51 | | 43 | | | | | 58454 | | B/S |
| 525.40 | 0.89 | | 0.75 | 44 | 56 | 0.42 | 58561 | 2:00 | Wall Loss Indication |
| 527.14 | 2.62 | | 0.75 | 68 | 32 | 0.24 | 58770 | 2:00 | Wall Loss Indication |
| 527.86 | 3.35 | | 0.75 | 50 | 50 | 0.37 | 58858 | 2:30 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 528.43 | 3.92 |  | 0.75 | 24 | 76 | 0.57 | 58926 | 9:00 | Wall Loss Indication |
| 531.62 | 7.10 |  | 0.75 | 35 | 65 | 0.49 | 59309 | 8:30 | Wall Loss Indication |
| 532.18 | 7.67 |  | 0.75 | 66 | 34 | 0.25 | 59377 | 2:00 | Wall Loss Indication |
| 533.30 | 8.79 |  | 0.75 | 41 | 59 | 0.44 | 59512 | 8:30 | Wall Loss Indication |
| 536.57 |  | 44 |  |  |  |  | 59905 |  | B/S |
| 537.84 | 1.27 |  | 0.75 | 46 | 54 | 0.40 | 60057 | 2:00 | Wall Loss Indication |
| 538.29 | 1.72 |  | 0.75 | 38 | 62 | 0.46 | 60111 | 7:00 | Wall Loss Indication |
| 539.14 | 2.56 |  | 0.75 | 60 | 40 | 0.30 | 60213 | 2:00 | Wall Loss Indication |
| 539.35 | 2.77 |  | 0.75 | 44 | 56 | 0.42 | 60239 | 12:00 | Wall Loss Indication |
| 543.49 | 6.91 |  | 0.75 | 36 | 64 | 0.48 | 60737 | 2:30 | Wall Loss Indication |
| 544.95 | 8.37 |  | 0.75 | 48 | 52 | 0.39 | 60912 | 2:30 | Wall Loss Indication |
| 545.64 | 9.07 |  | 0.75 | 42 | 58 | 0.43 | 60996 | 2:30 | Wall Loss Indication |
| 548.77 |  | 45 |  |  |  |  | 61371 |  | B/S |
| 550.39 | 1.63 |  | 0.75 | 34 | 66 | 0.49 | 61567 | 9:00 | Wall Loss Indication |
| 550.56 | 1.80 |  | 0.75 | 43 | 57 | 0.42 | 61588 | 2:00 | Wall Loss Indication |
| 551.46 | 2.69 |  | 0.75 | 51 | 49 | 0.37 | 61696 | 2:00 | Wall Loss Indication |
| 561.00 |  | 46 |  |  |  |  | 62843 |  | B/S |
| 563.37 | 2.37 |  | 0.75 | 40 | 60 | 0.45 | 63128 | 9:30 | Wall Loss Indication |
| 564.92 | 3.92 |  | 0.75 | 49 | 51 | 0.38 | 63314 | 1:00 | Wall Loss Indication |
| 569.06 | 8.06 |  | 0.75 | 64 | 36 | 0.27 | 63812 | 1:30 | Wall Loss Indication |
| 573.28 |  | 47 |  |  |  |  | 64320 |  | B/S |
| 575.84 | 2.55 |  | 0.75 | 39 | 61 | 0.46 | 64627 | 10:30 | Wall Loss Indication |
| 576.20 | 2.91 |  | 0.75 | 51 | 49 | 0.37 | 64670 | 1:30 | Wall Loss Indication |
| 576.85 | 3.57 |  | 0.75 | 46 | 54 | 0.40 | 64750 | 11:00 | Wall Loss Indication |
| 577.18 | 3.90 |  | 0.75 | 32 | 68 | 0.51 | 64789 | 1:30 | Wall Loss Indication |
| 579.34 | 6.06 |  | 0.75 | 45 | 55 | 0.41 | 65048 | 1:30 | Wall Loss Indication |
| 585.40 |  | 48 |  |  |  |  | 65778 |  | B/S |
| 587.19 | 1.79 |  | 0.75 | 46 | 54 | 0.40 | 65996 | 1:30 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 587.59 | 2.18 | | 0.75 | 33 | 67 | 0.50 | 66044 | 9:00 | Wall Loss Indication |
| 587.80 | 2.40 | | 0.75 | 38 | 62 | 0.47 | 66070 | 1:30 | Wall Loss Indication |
| 591.73 | 6.33 | | 0.75 | 20 | 80 | 0.60 | 66549 | 1:30 | Wall Loss Indication |
| 593.25 | 7.84 | | 0.75 | 22 | 78 | 0.59 | 66734 | 6:30 | Wall Loss Indication |
| 594.01 | 8.60 | | 0.75 | 25 | 75 | 0.56 | 66827 | 10:30 | Wall Loss Indication |
| 594.57 | 9.17 | | 0.75 | 64 | 36 | 0.27 | 66896 | 1:30 | Wall Loss Indication -Major |
| 597.59 | | 49 | | | | | 67265 | | B/S |
| 599.61 | 2.02 | | 0.75 | 43 | 57 | 0.43 | 67507 | 1:00 | Wall Loss Indication |
| 599.92 | 2.32 | | 0.75 | <20 | >80 | >0.6 | 67544 | 8:30 | Wall Loss Indication |
| 600.26 | 2.66 | | 0.75 | 32 | 68 | 0.51 | 67585 | 1:30 | Wall Loss Indication |
| 601.10 | 3.50 | | 0.75 | 29 | 71 | 0.53 | 67686 | 1:30 | Wall Loss Indication |
| 606.15 | 8.56 | | 0.75 | 24 | 76 | 0.57 | 68294 | 10:30 | Wall Loss Indication |
| 607.14 | 9.55 | | 0.75 | 30 | 70 | 0.53 | 68413 | 6:00 | Wall Loss Indication |
| 609.70 | | 50 | | | | | 68720 | | B/S |
| 612.39 | 2.69 | | 0.75 | 50 | 50 | 0.37 | 69044 | 1:30 | Wall Loss Indication |
| 613.15 | 3.45 | | 0.75 | 46 | 54 | 0.40 | 69135 | 2:00 | Wall Loss Indication |
| 616.74 | 7.04 | | 0.75 | 27 | 73 | 0.55 | 69567 | 11:00 | Wall Loss Indication |
| 617.64 | 7.94 | | 0.75 | 47 | 53 | 0.40 | 69675 | 5:00 | Wall Loss Indication |
| 619.67 | 9.98 | | 0.75 | 22 | 78 | 0.58 | 69920 | 11:00 | Wall Loss Indication |
| 620.71 | 11.02 | | 0.75 | <20 | >80 | >0.6 | 70045 | 4:30 | Wall Loss Indication |
| 621.93 | | 51 | | | | | 70192 | | B/S |
| 622.80 | 0.87 | | 0.75 | 41 | 59 | 0.44 | 70296 | 2:00 | Wall Loss Indication |
| 623.77 | 1.85 | | 0.75 | 47 | 53 | 0.40 | 70414 | 1:00 | Wall Loss Indication |
| 624.08 | 2.16 | | 0.75 | 38 | 62 | 0.47 | 70451 | 9:00 | Wall Loss Indication |
| 624.51 | 2.58 | | 0.75 | 33 | 67 | 0.50 | 70502 | 1:30 | Wall Loss Indication |
| 629.49 | 7.56 | | 0.75 | <20 | >80 | >0.6 | 71101 | 4:00 | Wall Loss Indication |
| 629.68 | 7.75 | | 0.75 | 42 | 58 | 0.43 | 71124 | 9:00 | Wall Loss Indication |
| 632.03 | 10.10 | | 0.75 | 21 | 79 | 0.59 | 71406 | 10:30 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 632.29 | 10.36 | | 0.75 | 22 | 78 | 0.59 | 71437 | 6:30 | Wall Loss Indication |
| 634.18 | | 52 | | | | | 71665 | | B/S |
| 635.12 | 0.93 | | 0.75 | 41 | 59 | 0.44 | 71780 | 1:30 | Wall Loss Indication |
| 636.24 | 2.05 | | 0.75 | 28 | 72 | 0.54 | 71918 | 8:30 | Wall Loss Indication |
| 637.21 | 3.03 | | 0.75 | 23 | 77 | 0.57 | 72038 | 8:30 | Wall Loss Indication |
| 642.26 | 8.08 | | 0.75 | 23 | 77 | 0.58 | 72661 | 6:30 | Wall Loss Indication |
| 643.40 | 9.22 | | 0.75 | <20 | >80 | >0.6 | 72801 | 4:00 | Wall Loss Indication |
| 646.37 | | 53 | | | | | 73167 | | B/S |
| 656.82 | 10.44 | | 0.75 | 38 | 62 | 0.46 | 74396 | 8:30 | Wall Loss Indication |
| 658.56 | | 54 | | | | | 74602 | | B/S |
| 661.85 | 3.29 | | 0.75 | <20 | >80 | >0.6 | 74998 | 1:00 | Wall Loss Indication |
| 668.46 | 9.90 | | 0.75 | 27 | 73 | 0.55 | 75792 | 3:30 | Wall Loss Indication |
| 670.78 | | 55 | | | | | 76072 | | B/S |
| 677.01 | 6.22 | | 0.75 | 20 | 80 | 0.60 | 76820 | 6:00 | Wall Loss Indication |
| 678.00 | 7.21 | | 0.75 | <20 | >80 | >0.6 | 76939 | 5:30 | Wall Loss Indication |
| 678.80 | 8.02 | | 0.75 | <20 | >80 | >0.6 | 77040 | 6:00 | Wall Loss Indication |
| 680.52 | 9.74 | | 0.75 | <20 | >80 | >0.6 | 77243 | 4:30 | Wall Loss Indication |
| 683.14 | | 56 | | | | | 77558 | | B/S |
| 684.94 | 1.79 | | 0.75 | 24 | 76 | 0.57 | 77773 | 4:00 | Wall Loss Indication |
| 692.78 | 9.63 | | 0.75 | 31 | 69 | 0.52 | 78711 | 9:00 | Wall Loss Indication |
| 695.33 | | 57 | | | | | 79017 | | B/S |
| 697.32 | 1.99 | | 0.75 | 38 | 62 | 0.47 | 79256 | 8:00 | Wall Loss Indication |
| 697.84 | 2.50 | | 0.75 | <20 | >80 | >0.6 | 79319 | 10:30 | Wall Loss Indication |
| 698.26 | 2.93 | | 0.75 | 27 | 73 | 0.55 | 79370 | 5:30 | Wall Loss Indication |
| 707.63 | | 58 | | | | | 80496 | | B/S |
| 710.20 | 2.57 | | 0.75 | <20 | >80 | >0.6 | 80805 | 3:30 | Wall Loss Indication |
| 711.00 | 3.37 | | 0.75 | 28 | 72 | 0.54 | 80901 | 2:30 | Wall Loss Indication |
| 719.79 | | 59 | | | | | 81959 | | B/S |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 722.29 | 2.50 |  | 0.75 | 55 | 45 | 0.33 | 82260 | 9:00 | Wall Loss Indication |
| 727.55 | 7.76 |  | 0.75 | 63 | 37 | 0.28 | 82892 | 1:00 | Wall Loss Indication |
| 728.00 | 8.21 |  | 0.75 | 63 | 37 | 0.28 | 82946 | 1:00 | Wall Loss Indication |
| 729.16 | 9.37 |  | 0.75 | 22 | 78 | 0.59 | 83085 | 3:30 | Wall Loss Indication |
| 729.76 | 9.97 |  | 0.75 | 47 | 53 | 0.40 | 83158 | 1:30 | Wall Loss Indication |
| 732.00 |  | 60 |  |  |  |  | 83427 |  | B/S |
| 733.56 | 1.56 |  | 0.75 | 49 | 51 | 0.39 | 83615 | 1:30 | Wall Loss Indication |
| 738.67 | 6.66 |  | 0.75 | 39 | 61 | 0.46 | 84229 | 2:00 | Wall Loss Indication |
| 741.34 | 9.34 |  | 0.75 | 49 | 51 | 0.39 | 84551 | 1:00 | Wall Loss Indication |
| 744.22 |  | 61 |  |  |  |  | 84897 |  | B/S |
| 746.53 | 2.30 |  | 0.75 | 46 | 54 | 0.41 | 85175 | 1:00 | Wall Loss Indication |
| 748.20 | 3.98 |  | 0.75 | 40 | 60 | 0.45 | 85376 | 12:00 | Wall Loss Indication |
| 752.41 | 8.19 |  | 0.75 | 36 | 64 | 0.48 | 85883 | 10:30 | Wall Loss Indication |
| 752.71 | 8.49 |  | 0.75 | 21 | 79 | 0.59 | 85919 | 8:00 | Wall Loss Indication |
| 754.47 | 10.25 |  | 0.75 | <20 | >80 | >0.6 | 86130 | 5:30 | Wall Loss Indication |
| 756.43 |  | 62 |  |  |  |  | 86365 |  | B/S |
| 758.90 | 2.47 |  | 0.75 | 60 | 40 | 0.30 | 86663 | 0:30 | Wall Loss Indication |
| 759.82 | 3.39 |  | 0.75 | 44 | 56 | 0.42 | 86773 | 0:30 | Wall Loss Indication |
| 763.17 | 6.74 |  | 0.75 | 42 | 58 | 0.43 | 87176 | 1:00 | Wall Loss Indication |
| 763.40 | 6.97 |  | 0.75 | 32 | 68 | 0.51 | 87204 | 0:00 | Wall Loss Indication |
| 764.70 | 8.27 |  | 0.75 | 23 | 77 | 0.58 | 87360 | 0:30 | Wall Loss Indication |
| 765.25 | 8.82 |  | 0.75 | <20 | >80 | >0.6 | 87426 | 5:30 | Wall Loss Indication |
| 765.43 | 9.00 |  | 0.75 | 44 | 56 | 0.42 | 87448 | 1:00 | Wall Loss Indication |
| 768.64 |  | 63 |  |  |  |  | 87834 |  | B/S |
| 770.60 | 1.96 |  | 0.75 | 23 | 77 | 0.58 | 88070 | 1:00 | Wall Loss Indication |
| 771.43 | 2.79 |  | 0.75 | 26 | 74 | 0.56 | 88170 | 1:00 | Wall Loss Indication |
| 771.76 | 3.12 |  | 0.75 | 48 | 52 | 0.39 | 88209 | 3:00 | Wall Loss Indication |
| 774.75 | 6.12 |  | 0.75 | 36 | 64 | 0.48 | 88570 | 1:00 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 775.08 | 6.45 | | 0.75 | 43 | 57 | 0.43 | 88609 | 3:00 | Wall Loss Indication |
| 778.21 | 9.57 | | 0.75 | 25 | 75 | 0.56 | 88985 | 2:00 | Wall Loss Indication |
| 780.84 | | 64 | | | | | 89301 | | B/S |
| 782.04 | 1.20 | | 0.75 | 24 | 76 | 0.57 | 89446 | 0:00 | Wall Loss Indication |
| 783.17 | 2.32 | | 0.75 | 44 | 56 | 0.42 | 89581 | 0:30 | Wall Loss Indication |
| 784.16 | 3.32 | | 0.75 | 32 | 68 | 0.51 | 89701 | 6:00 | Wall Loss Indication |
| 784.19 | 3.35 | | 0.75 | 42 | 58 | 0.43 | 89705 | 4:00 | Wall Loss Indication |
| 785.58 | 4.74 | | 0.75 | 59 | 41 | 0.31 | 89871 | 3:30 | Wall Loss Indication |
| 789.53 | 8.69 | | 0.75 | 32 | 68 | 0.51 | 90347 | 5:30 | Wall Loss Indication |
| 790.10 | 9.26 | | 0.75 | <20 | >80 | >0.6 | 90415 | 2:00 | Wall Loss Indication |
| 790.46 | 9.62 | | 0.75 | 23 | 77 | 0.58 | 90458 | 10:30 | Wall Loss Indication |
| 792.97 | | 65 | | | | | 90761 | | B/S |
| 795.03 | 2.06 | | 0.75 | 37 | 63 | 0.47 | 91008 | 0:30 | Wall Loss Indication |
| 795.51 | 2.53 | | 0.75 | 34 | 66 | 0.50 | 91065 | 0:30 | Wall Loss Indication |
| 795.78 | 2.80 | | 0.75 | <20 | >80 | >0.6 | 91098 | 3:00 | Wall Loss Indication |
| 797.40 | 4.43 | | 0.75 | 63 | 37 | 0.28 | 91294 | 0:30 | Wall Loss Indication |
| 798.97 | 6.00 | | 0.75 | 33 | 67 | 0.50 | 91482 | 0:30 | Wall Loss Indication |
| 799.72 | 6.74 | | 0.75 | 36 | 64 | 0.48 | 91572 | 0:30 | Wall Loss Indication |
| 800.85 | 7.87 | | 0.75 | 22 | 78 | 0.58 | 91707 | 3:30 | Wall Loss Indication |
| 800.94 | 7.97 | | 0.75 | 36 | 64 | 0.48 | 91719 | 1:30 | Wall Loss Indication |
| 802.27 | 9.30 | | 0.75 | 39 | 61 | 0.46 | 91879 | 1:00 | Wall Loss Indication |
| 803.16 | 10.19 | | 0.75 | <20 | >80 | >0.6 | 91986 | 6:00 | Wall Loss Indication |
| 805.18 | | 66 | | | | | 92228 | | B/S |
| 807.55 | 2.37 | | 0.75 | 24 | 76 | 0.57 | 92514 | 3:30 | Wall Loss Indication |
| 808.83 | 3.65 | | 0.75 | 24 | 76 | 0.57 | 92668 | 3:00 | Wall Loss Indication |
| 814.59 | 9.42 | | 0.75 | <20 | >80 | >0.6 | 93361 | 3:00 | Wall Loss Indication |
| 815.08 | 9.91 | | 0.75 | 51 | 49 | 0.37 | 93420 | 5:30 | Wall Loss Indication - Major |
| 817.31 | | 67 | | | | | 93687 | | B/S |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remainin g | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 819.10 | 1.80 | | 0.75 | 31 | 69 | 0.52 | 93904 | 8:00 | Wall Loss Indication |
| 819.20 | 1.90 | | 0.75 | 26 | 74 | 0.55 | 93915 | 10:30 | Wall Loss Indication |
| 823.49 | 6.19 | | 0.75 | 59 | 41 | 0.31 | 94432 | 12:30 | Wall Loss Indication |
| 824.84 | 7.53 | | 0.75 | 48 | 52 | 0.39 | 94594 | 12:30 | Wall Loss Indication |
| 826.56 | 9.25 | | 0.75 | 30 | 70 | 0.53 | 94800 | 12:30 | Wall Loss Indication |
| 829.75 | | 68 | | | | | 95184 | | B/S |
| 833.04 | 3.29 | | 0.75 | 34 | 66 | 0.50 | 95580 | 12:30 | Wall Loss Indication |
| 839.47 | 9.72 | | 0.75 | 29 | 71 | 0.54 | 96353 | 7:30 | Wall Loss Indication |
| 841.87 | | 69 | | | | | 96642 | | B/S |
| 843.05 | 1.18 | | 0.75 | 20 | 80 | 0.60 | 96784 | 12:30 | Wall Loss Indication |
| 844.39 | 2.52 | | 0.75 | <20 | >80 | >0.6 | 96945 | 12:30 | Wall Loss Indication |
| 845.49 | 3.62 | | 0.75 | 32 | 68 | 0.51 | 97077 | 12:30 | Wall Loss Indication |
| 847.74 | 5.87 | | 0.75 | 52 | 48 | 0.36 | 97347 | 8:00 | Wall Loss Indication |
| 854.04 | | 70 | | | | | 98105 | | B/S |
| 861.01 | 6.97 | | 0.75 | 35 | 65 | 0.48 | 98943 | 11:30 | Wall Loss Indication |
| 862.01 | 7.97 | | 0.75 | 44 | 56 | 0.42 | 99064 | 11:30 | Wall Loss Indication |
| 863.82 | 9.79 | | 0.75 | 33 | 67 | 0.51 | 99282 | 5:00 | Wall Loss Indication |
| 866.35 | | 71 | | | | | 99585 | | B/S |
| 868.91 | 2.56 | | 0.75 | 24 | 76 | 0.57 | 99894 | 3:30 | Wall Loss Indication |
| 878.53 | | 72 | | | | | 101051 | | B/S |
| 885.41 | 6.88 | | 0.75 | 23 | 77 | 0.58 | 101879 | 8:00 | Wall Loss Indication |
| 889.22 | 10.69 | | 0.75 | 25 | 75 | 0.56 | 102336 | 8:00 | Wall Loss Indication |
| 890.81 | | 73 | | | | | 102528 | | B/S |
| 893.39 | 2.57 | | 0.75 | 26 | 74 | 0.56 | 102837 | 8:00 | Wall Loss Indication |
| 897.61 | 6.79 | | 0.75 | 24 | 76 | 0.57 | 103345 | 12:30 | Wall Loss Indication |
| 903.06 | | 74 | | | | | 104002 | | B/S |
| 905.56 | 2.49 | | 0.75 | 27 | 73 | 0.55 | 104302 | 11:30 | Wall Loss Indication |
| 909.37 | 6.31 | | 0.75 | 21 | 79 | 0.59 | 104760 | 9:30 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 909.99 | 6.92 | | 0.75 | <20 | >80 | >0.6 | 104834 | 5:00 | Wall Loss Indication |
| 912.17 | 9.11 | | 0.75 | <20 | >80 | >0.6 | 105097 | 9:30 | Wall Loss Indication |
| 915.11 | | 75 | | | | | 105450 | | B/S |
| 917.65 | 2.54 | | 0.75 | 27 | 73 | 0.55 | 105756 | 4:30 | Wall Loss Indication |
| 917.73 | 2.62 | | 0.75 | <20 | >80 | >0.6 | 105766 | 3:30 | Wall Loss Indication -part of the same WL |
| 918.74 | 3.63 | | 0.75 | 27 | 73 | 0.54 | 105887 | 2:30 | Wall Loss Indication |
| 927.29 | | 76 | | | | | 106915 | | B/S |
| 939.47 | | 77 | | | | | 108380 | | B/S |
| 942.79 | 3.31 | | 0.75 | 22 | 78 | 0.59 | 108779 | 5:30 | Wall Loss Indication |
| 947.92 | 8.45 | | 0.75 | 21 | 79 | 0.60 | 109397 | 7:30 | Wall Loss Indication |
| 948.50 | 9.03 | | 0.75 | 36 | 64 | 0.48 | 109466 | 4:30 | Wall Loss Indication |
| 951.81 | | 78 | | | | | 109865 | | B/S |
| 954.21 | 2.39 | | 0.75 | 26 | 74 | 0.55 | 110153 | 1:00 | Wall Loss Indication |
| 963.88 | | 79 | | | | | 111316 | | B/S |
| 970.44 | 6.57 | | 0.75 | 30 | 70 | 0.52 | 112105 | 4:30 | Wall Loss Indication - Major |
| 971.57 | 7.69 | | 0.75 | 28 | 72 | 0.54 | 112241 | 11:30 | Wall Loss Indication |
| 973.86 | 9.98 | | 0.75 | 25 | 75 | 0.56 | 112515 | 11:00 | Wall Loss Indication |
| 976.15 | | 80 | | | | | 112791 | | B/S |
| 983.37 | 7.22 | | 0.75 | 35 | 65 | 0.49 | 113660 | 4:30 | Wall Loss Indication |
| 986.19 | 10.04 | | | | | | 113999 | | Line Feature: possible Valve |
| 988.66 | | 81 | | | | | 114296 | | B/S |
| 990.60 | 1.94 | | 0.75 | <20 | >80 | >0.6 | 114529 | 9:30 | Wall Loss Indication |
| 990.72 | 2.06 | | 0.75 | <20 | >80 | >0.6 | 114543 | 3:30 | Wall Loss Indication |
| 991.11 | 2.44 | | 0.75 | 27 | 73 | 0.55 | 114590 | 7:30 | Wall Loss Indication |
| 1000.58 | | 82 | | | | | 115730 | | B/S |
| 1002.74 | 2.16 | | 0.75 | 26 | 74 | 0.56 | 115989 | 8:30 | Wall Loss Indication |
| 1003.67 | 3.08 | | 0.75 | 23 | 77 | 0.58 | 116101 | 8:30 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 1010.32 | 9.74 | | 0.75 | <20 | >80 | >0.6 | 116901 | 7:00 | Wall Loss Indication |
| 1012.84 | | 83 | | | | | 117204 | | B/S |
| 1025.07 | | 84 | | | | | 118675 | | B/S (Tee or Branch?) |
| 1037.26 | | 85 | | | | | 120155 | | B/S |
| 1049.32 | | 86 | | | | | 121605 | | B/S |
| 1053.14 | 3.82 | | 0.75 | 34 | 66 | 0.49 | 122065 | 4:00 | Wall Loss Indication |
| 1056.81 | 7.49 | | 0.75 | 52 | 48 | 0.36 | 122507 | 8:30 | Wall Loss Indication |
| 1061.38 | | 87 | | | | | 123056 | | B/S |
| 1073.56 | | 88 | | | | | 124520 | | B/S |
| 1082.88 | 9.32 | | 0.75 | <20 | >80 | >0.6 | 125641 | 4:00 | Wall Loss Indication |
| 1085.68 | | 89 | | | | | 125978 | | B/S |
| 1090.81 | | | | | | | 126595 | | Very noisy data right after B&S lasting for about 69-inches |
| 1095.44 | 9.76 | | 0.75 | <20 | >80 | >0.6 | 127152 | 12:30 | Wall Loss Indication |
| 1097.91 | | 90 | | | | | 127449 | | B/S |
| 1100.16 | 2.24 | | 0.75 | <20 | >80 | >0.6 | 127720 | 12:30 | Wall Loss Indication |
| 1107.42 | 9.51 | | 0.75 | 27 | 73 | 0.55 | 128593 | 5:30 | Wall Loss Indication |
| 1110.06 | | 91 | | | | | 128911 | | B/S |
| 1122.16 | | 92 | | | | | 130366 | | B/S |
| 1134.35 | | 93 | | | | | 132162 | | B/S |
| 1146.54 | | 94 | | | | | 133205 | | B/S |
| 1152.10 | 5.56 | | 0.75 | 22 | 78 | 0.59 | 133957 | 3:30 | Wall Loss Indication |
| 1154.42 | 7.89 | | 0.75 | 36 | 64 | 0.48 | 134271 | 3:30 | Wall Loss Indication |
| 1155.49 | 8.95 | | 0.75 | 35 | 65 | 0.49 | 134415 | 3:30 | Wall Loss Indication |
| 1158.72 | | 95 | | | | | 134854 | | B/S |
| 1161.33 | 2.61 | | 0.75 | 32 | 68 | 0.51 | 135148 | 2:30 | Wall Loss Indication |
| 1166.22 | 7.50 | | 0.75 | 29 | 71 | 0.53 | 135699 | 2:00 | Wall Loss Indication |
| 1167.46 | 8.73 | | 0.75 | 30 | 70 | 0.52 | 135839 | 1:00 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 1168.95 | 10.22 | | 0.75 | 49 | 51 | 0.39 | 136007 | 1:30 | Wall Loss Indication |
| 1170.91 | | 96 | | | | | 136229 | | B/S |
| 1172.35 | 1.44 | | 0.75 | 23 | 77 | 0.58 | 136400 | 9:00 | Wall Loss Indication |
| 1177.33 | 6.41 | | 0.75 | 20 | 80 | 0.60 | 136993 | 4:30 | Wall Loss Indication |
| 1178.59 | 7.68 | | 0.75 | 50 | 50 | 0.37 | 137144 | 5:30 | Wall Loss Indication |
| 1183.10 | | 97 | | | | | 137682 | | B/S |
| 1185.43 | 2.32 | | 0.75 | 35 | 65 | 0.49 | 137961 | 1:30 | Wall Loss Indication |
| 1195.31 | | 98 | | | | | 139150 | | B/S |
| 1207.64 | | 99 | | | | | 140633 | | B/S |
| 1219.78 | | 100 | | | | | 142093 | | B/S |
| 1223.33 | 3.55 | | 0.75 | 28 | 72 | 0.54 | 142520 | 6:00 | Wall Loss Indication |
| 1227.06 | 7.28 | | 0.75 | 24 | 76 | 0.57 | 142969 | 5:00 | Wall Loss Indication |
| 1231.92 | | 101 | | | | | 143553 | | B/S |
| 1240.40 | 8.48 | | 0.75 | 28 | 72 | 0.54 | 144573 | 1:00 | Wall Loss Indication |
| 1241.14 | 9.22 | | 0.75 | 26 | 74 | 0.56 | 144662 | 1:30 | Wall Loss Indication |
| 1244.14 | | 102 | | | | | 145022 | | B/S |
| 1246.38 | 2.24 | | 0.75 | <20 | >80 | >0.6 | 145292 | 12:00 | Wall Loss Indication |
| 1251.43 | 7.29 | | 0.75 | <20 | >80 | >0.6 | 145900 | 4:30 | Wall Loss Indication |
| 1253.76 | 9.63 | | 0.75 | <20 | >80 | >0.6 | 146180 | 12:30 | Wall Loss Indication |
| 1256.30 | | 103 | | | | | 146485 | | B/S |
| 1258.52 | 2.22 | | 0.75 | 24 | 76 | 0.57 | 146753 | 3:00 | Wall Loss Indication |
| 1266.84 | 10.55 | | 0.75 | <20 | >80 | >0.6 | 147754 | 11:30 | Wall Loss Indication |
| 1268.54 | | 104 | | | | | 147958 | | B/S |
| 1280.85 | | 105 | | | | | 149438 | | Possible Slightly Open B/S |
| 1283.06 | 14.52 | | 0.75 | 22 | 78 | 0.58 | 149704 | 11:30 | Wall Loss Indication |
| 1290.61 | 22.07 | | 0.75 | 27 | 73 | 0.55 | 150612 | 11:30 | Wall Loss Indication |
| 1292.94 | | 106 | | | | | 150892 | | B/S |
| 1295.53 | 2.59 | | 0.75 | 24 | 76 | 0.57 | 151204 | 11:30 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 1305.05 | | 107 | | | | | 152348 | | B/S |
| 1317.24 | | 108 | | | | | 153774 | | B/S |
| 1327.03 | 9.79 | | 0.75 | 30 | 70 | 0.53 | 154951 | 10:30 | Wall Loss Indication |
| 1329.35 | | 109 | | | | | 155231 | | B/S |
| 1332.34 | 2.99 | | 0.75 | 22 | 78 | 0.58 | 155591 | 7:30 | Wall Loss Indication |
| 1336.47 | 7.12 | | 0.75 | <20 | >80 | >0.6 | 156088 | 5:30 | Wall Loss Indication |
| 1338.12 | 8.77 | | 0.75 | 20 | 80 | 0.60 | 156286 | 9:30 | Wall Loss Indication |
| 1338.97 | 9.62 | | 0.75 | <20 | >80 | >0.6 | 156388 | 5:00 | Wall Loss Indication |
| 1341.48 | | 110 | | | | | 156690 | | B/S |
| 1348.77 | 7.28 | | 0.75 | 21 | 79 | 0.59 | 157566 | 11:30 | Wall Loss Indication |
| 1350.26 | 8.78 | | 0.75 | 25 | 75 | 0.56 | 157746 | 9:30 | Wall Loss Indication |
| 1351.46 | 9.98 | | 0.75 | 33 | 67 | 0.51 | 157890 | 9:30 | Wall Loss Indication |
| 1353.72 | | 111 | | | | | 158161 | | B/S |
| 1355.99 | 2.27 | | 0.75 | 20 | 80 | 0.60 | 158435 | 11:00 | Wall Loss Indication |
| 1356.94 | 3.22 | | 0.75 | 36 | 64 | 0.48 | 158549 | 5:30 | Wall Loss Indication |
| 1362.50 | 8.78 | | 0.75 | <20 | >80 | >0.6 | 159217 | 6:00 | Wall Loss Indication |
| 1365.85 | | 112 | | | | | 159620 | | B/S |
| 1368.06 | 2.22 | | 0.75 | <20 | >80 | >0.6 | 159887 | 11:00 | Wall Loss Indication |
| 1372.96 | 7.11 | | 0.75 | 24 | 76 | 0.57 | 160476 | 10:30 | Wall Loss Indication |
| 1372.99 | 7.14 | | 0.75 | 24 | 76 | 0.57 | 160479 | 3:30 | Wall Loss Indication |
| 1377.99 | | 113 | | | | | 161081 | | B/S |
| 1380.50 | 2.51 | | 0.75 | 20 | 80 | 0.60 | 161383 | 11:00 | Wall Loss Indication |
| 1390.16 | | 114 | | | | | 162545 | | B/S |
| 1402.36 | | 115 | | | | | 164011 | | B/S |
| 1411.19 | 8.83 | | 0.75 | <20 | >80 | >0.6 | 165073 | 10:00 | Wall Loss Indication |
| 1414.49 | | 116 | | | | | 165470 | | B/S |
| 1426.62 | | 117 | | | | | 166929 | | B/S |
| 1438.81 | | 118 | | | | | 168430 | | B/S |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 1450.94 | | 119 | | | | | 169889 | | B/S |
| 1458.26 | 7.31 | | 0.75 | <20 | >80 | >0.6 | 170768 | 10:00 | Wall Loss Indication |
| 1461.16 | 10.22 | | 0.75 | 51 | 49 | 0.37 | 171118 | 12:30 | Wall Loss Indication |
| 1463.16 | | 120 | | | | | 171359 | | B/S |
| 1475.34 | | 121 | | | | | 172823 | | B/S |
| 1487.48 | | 122 | | | | | 174283 | | B/S |
| 1499.68 | | 123 | | | | | 175751 | | Possible Open B/S |
| 1511.90 | | 124 | | | | | 177219 | | B/S |
| 1520.38 | 8.48 | | 0.75 | <20 | >80 | >0.6 | 178239 | 9:30 | Wall Loss Indication |
| 1524.04 | | 125 | | | | | 178680 | | B/S |
| 1536.23 | | 126 | | | | | 180146 | | B/S |
| 1538.45 | 2.22 | | 0.75 | <20 | >80 | >0.6 | 180413 | 10:00 | Wall Loss Indication |
| 1543.45 | 7.22 | | 0.75 | <20 | >80 | >0.6 | 181015 | 3:00 | Wall Loss Indication |
| 1545.73 | 9.50 | | 0.75 | <20 | >80 | >0.6 | 181289 | 3:00 | Wall Loss Indication |
| 1548.40 | | 127 | | | | | 181610 | | B/S |
| 1560.66 | | 128 | | | | | 183084 | | B/S |
| 1572.86 | | 129 | | | | | 184551 | | B/S |
| 1579.09 | 6.24 | | 0.75 | 27 | 73 | 0.55 | 185302 | 5:00 | Wall Loss Indication |
| 1585.00 | | 130 | | | | | 186012 | | B/S |
| 1588.35 | | | | | | | 186415 | 11:00 | Noisy data from 1588.4ft to 1590.7ft |
| 1591.17 | 6.17 | | 0.75 | 53 | 47 | 0.35 | 186753 | 10:00 | Wall Loss Indication |
| 1594.27 | | | | | | | 187127 | 11:00 | Noisy data from 1594.3 to 1595.4ft |
| 1597.20 | | 131 | | | | | 187480 | | B/S |
| 1609.52 | | 132 | | | | | 188961 | | B/S |
| 1621.71 | | 133 | | | | | 190425 | | B/S |
| 1629.75 | 8.04 | | 0.75 | 25 | 75 | 0.56 | 191328 | 7:30 | Wall Loss Indication |
| 1633.90 | | 134 | | | | | 191794 | | B/S |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 1640.85 | 6.95 |  | 0.75 | 29 | 71 | 0.53 | 192570 | 4:30 | Wall Loss Indication |
| 1646.09 |  | 135 |  |  |  |  | 193156 |  | B/S |
| 1647.89 | 1.80 |  | 0.75 | <20 | >80 | >0.6 | 193372 | 5:00 | Wall Loss Indication |
| 1648.84 | 2.74 |  | 0.75 | 26 | 74 | 0.55 | 193486 | 5:30 | Wall Loss Indication |
| 1654.36 | 8.27 |  | 0.75 | 43 | 57 | 0.43 | 194150 | 5:30 | Wall Loss Indication |
| 1655.79 | 9.70 |  | 0.75 | 28 | 72 | 0.54 | 194322 | 5:30 | Wall Loss Indication |
| 1658.28 |  | 136 |  |  |  |  | 194622 |  | B/S |
| 1666.05 | 7.76 |  | 0.75 | <20 | >80 | >0.6 | 195556 | 4:30 | Wall Loss Indication |
| 1668.60 | 10.32 |  |  |  |  |  | 195863 |  | Valve |
| 1670.48 |  | 137 |  |  |  |  | 196088 |  | B/S |
| 1673.90 | 3.42 |  | 0.75 | 45 | 55 | 0.41 | 196500 | 9:30 | Wall Loss Indication |
| 1678.19 | 7.71 |  | 0.75 | 23 | 77 | 0.58 | 197016 | 5:00 | Wall Loss Indication |
| 1679.14 | 8.66 |  | 0.75 | <20 | >80 | >0.6 | 197130 | 9:30 | Wall Loss Indication |
| 1682.71 |  | 138 |  |  |  |  | 197559 |  | B/S |
| 1692.19 | 9.48 |  |  |  |  |  | 198699 |  | Line feature - Branch? |
| 1694.80 |  | 139 |  |  |  |  | 199014 |  | B/S |
| 1697.09 | 2.28 |  | 0.75 | <20 | >80 | >0.6 | 199289 | 8:00 | Wall Loss Indication |
| 1697.59 | 2.78 |  | 0.75 | 37 | 63 | 0.47 | 199349 | 5:00 | Wall Loss Indication |
| 1706.89 |  | 140 |  |  |  |  | 200467 |  | B/S |
| 1709.15 | 2.26 |  | 0.75 | <20 | >80 | >0.6 | 200740 | 9:00 | Wall Loss Indication |
| 1715.29 | 8.40 |  | 0.75 | <20 | >80 | >0.6 | 201477 | 9:30 | Wall Loss Indication |
| 1719.04 |  | 141 |  |  |  |  | 201929 |  | B/S |
| 1721.59 | 2.55 |  | 0.75 | <20 | >80 | >0.6 | 202219 | 8:30 | Wall Loss Indication |
| 1731.23 |  | 142 |  |  |  |  | 203316 |  | B/S |
| 1737.30 | 6.08 |  | 0.75 | 29 | 71 | 0.54 | 204047 | 9:30 | Wall Loss Indication |
| 1739.79 | 8.56 |  | 0.75 | 40 | 60 | 0.45 | 204345 | 8:30 | Wall Loss Indication |
| 1743.57 |  | 143 |  |  |  |  | 204800 |  | B/S |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 1747.09 | | | | | | | 205224 | | Noisy data from 1747.1ft to 1753.5ft |
| 1755.53 | | 144 | | | | | 206239 | | B/S |
| 1758.26 | | | | | | | 206567 | | Noisy data from 1758.3ft to 1764.2ft |
| 1767.79 | | 145 | | | | | 207714 | | B/S |
| 1774.42 | 6.63 | | 0.75 | <20 | >80 | >0.6 | 208498 | 5:00 | Wall Loss Indication |
| 1775.28 | 7.49 | | 0.75 | <20 | >80 | >0.6 | 208599 | 6:30 | Wall Loss Indication |
| 1775.45 | 7.65 | | 0.75 | <20 | >80 | >0.6 | 208619 | 8:00 | Wall Loss Indication |
| 1779.98 | | 146 | | | | | 209155 | | B/S |
| 1786.98 | 6.99 | | 0.75 | <20 | >80 | >0.6 | 209996 | 6:30 | Wall Loss Indication |
| 1792.14 | | 147 | | | | | 210617 | | B/S |
| 1796.46 | 4.32 | | | | | | 211136 | | Hydrant Branch |
| 1800.46 | 8.32 | | 0.75 | <20 | >80 | >0.6 | 211618 | 3:00 | Wall Loss Indication |
| 1800.48 | 8.34 | | 0.75 | 24 | 76 | 0.57 | 211620 | 5:30 | Wall Loss Indication |
| 1802.10 | 9.97 | | 0.75 | <20 | >80 | >0.6 | 211815 | 6:00 | Wall Loss Indication |
| 1804.38 | | 148 | | | | | 212089 | | B/S |
| 1806.66 | 2.28 | | 0.75 | <20 | >80 | >0.6 | 212364 | 9:30 | Wall Loss Indication |
| 1811.46 | 7.08 | | 0.75 | <20 | >80 | >0.6 | 212941 | 10:30 | Wall Loss Indication |
| 1816.56 | | 149 | | | | | 213554 | | B/S |
| 1819.36 | 2.79 | | 0.75 | <20 | >80 | >0.6 | 213890 | 2:00 | Wall Loss Indication |
| 1825.11 | 8.55 | | 0.75 | 29 | 71 | 0.53 | 214583 | 4:00 | Wall Loss Indication |
| 1826.29 | 9.73 | | 0.75 | <20 | >80 | >0.6 | 214724 | 1:30 | Wall Loss Indication |
| 1828.66 | | 150 | | | | | 215010 | | B/S |
| 1830.32 | 1.66 | | 0.75 | <20 | >80 | >0.6 | 215209 | 7:30 | Wall Loss Indication |
| 1835.57 | 6.90 | | 0.75 | <20 | >80 | >0.6 | 215840 | 3:30 | Wall Loss Indication |
| 1837.57 | 8.91 | | 0.75 | <20 | >80 | >0.6 | 216081 | 3:30 | Wall Loss Indication |
| 1840.98 | | 151 | | | | | 216491 | | B/S |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 1848.84 | 7.86 |  | 0.75 | 26 | 74 | 0.56 | 217436 | 4:00 | Wall Loss Indication - string of several shallow indications |
| 1850.49 | 9.52 |  | 0.75 | 25 | 75 | 0.56 | 217636 | 8:30 | Wall Loss Indication |
| 1853.19 |  | 152 |  |  |  |  | 217959 |  | B/S |
| 1855.11 | 1.93 |  | 0.75 | <20 | >80 | >0.6 | 218191 | 4:30 | Wall Loss Indication |
| 1855.37 | 2.19 |  | 0.75 | <20 | >80 | >0.6 | 218222 | 8:30 | Wall Loss Indication |
| 1861.66 | 8.47 |  | 0.75 | 22 | 78 | 0.58 | 218978 | 4:00 | Wall Loss Indication |
| 1865.37 |  | 153 |  |  |  |  | 219425 |  | B/S |
| 1867.67 | 2.29 |  | 0.75 | <20 | >80 | >0.6 | 219701 | 1:30 | Wall Loss Indication |
| 1872.60 | 7.22 |  | 0.75 | <20 | >80 | >0.6 | 220294 | 9:30 | Wall Loss Indication |
| 1872.83 | 7.46 |  | 0.75 | <20 | >80 | >0.6 | 220322 | 5:00 | Wall Loss Indication |
| 1877.53 |  | 154 |  |  |  |  | 220887 |  | B/S |
| 1878.99 | 1.46 |  | 0.75 | 32 | 68 | 0.51 | 221063 | 4:30 | Wall Loss Indication |
| 1880.18 | 2.64 |  | 0.75 | <20 | >80 | >0.6 | 221205 | 9:30 | Wall Loss Indication |
| 1884.05 | 6.52 |  | 0.75 | 26 | 74 | 0.56 | 221671 | 3:30 | Wall Loss Indication |
| 1887.04 | 9.51 |  | 0.75 | <20 | >80 | >0.6 | 222031 | 8:00 | Wall Loss Indication |
| 1889.76 |  | 155 |  |  |  |  | 222357 |  | B/S |
| 1892.67 | 2.91 |  | 0.75 | <20 | >80 | >0.6 | 222708 | 4:00 | Wall Loss Indication |
| 1897.15 | 7.39 |  | 0.75 | <20 | >80 | >0.6 | 223247 | 4:00 | Wall Loss Indication |
| 1902.03 |  | 156 |  |  |  |  | 223833 |  | B/S |
| 1904.47 | 2.44 |  | 0.75 | <20 | >80 | >0.6 | 224128 | 3:30 | Wall Loss Indication |
| 1904.69 | 2.66 |  | 0.75 | <20 | >80 | >0.6 | 224154 | 8:00 | Wall Loss Indication |
| 1914.24 |  | 157 |  |  |  |  | 225302 |  | B/S |
| 1922.33 | 8.09 |  | 0.75 | <20 | >80 | >0.6 | 226275 | 2:30 | Wall Loss Indication |
| 1923.96 | 9.72 |  | 0.75 | <20 | >80 | >0.6 | 226471 | 8:30 | Wall Loss Indication |
| 1926.41 |  | 158 |  |  |  |  | 226766 |  | B/S |
| 1936.27 |  |  |  |  |  |  | 227971 | 3:30 | Noisy data at 2:30 for most of joint |
| 1936.27 | 9.86 |  | 0.75 | <20 | >80 | >0.6 | 227971 | 6:30 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 1938.60 | | 159 | | | | | 228255 | | B/S |
| 1946.15 | | | | | | | 229163 | | Noisy data at 2:30 for most of joint |
| 1946.15 | 7.54 | | 0.75 | 20 | 80 | 0.60 | 229163 | 2:00 | Wall Loss Indication |
| 1947.21 | 8.61 | | 0.75 | <20 | >80 | >0.6 | 229291 | 6:30 | Wall Loss Indication |
| 1950.73 | | 160 | | | | | 229713 | | B/S |
| 1956.99 | | | | | | | 230467 | 3:30 | Noisy data at 2:30 for first 4ft joint |
| 1956.99 | 6.27 | | 0.75 | 23 | 77 | 0.58 | 230467 | 3:30 | Wall Loss Indication |
| 1962.86 | | 161 | | | | | 231173 | | B/S |
| 1971.39 | 8.53 | | 0.75 | <20 | >80 | >0.6 | 232230 | 8:30 | Wall Loss Indication |
| 1975.05 | | 162 | | | | | 232684 | | B/S |
| 1975.06 | | | | | | | 232685 | | Noisy data at 2:30 for most of joint |
| 1977.59 | 2.55 | | 0.75 | 21 | 79 | 0.59 | 232977 | 9:30 | Wall Loss Indication |
| 1981.65 | 6.60 | | 0.75 | 24 | 76 | 0.57 | 233446 | 2:30 | Wall Loss Indication |
| 1983.05 | 8.00 | | 0.75 | 28 | 72 | 0.54 | 233607 | 2:30 | Wall Loss Indication |
| 1987.24 | | 163 | | | | | 234091 | | B/S |
| 1989.12 | 1.89 | | 0.75 | 27 | 73 | 0.55 | 234323 | 3:00 | Wall Loss Indication |
| 1994.83 | 7.60 | | 0.75 | <20 | >80 | >0.6 | 235023 | 3:30 | Wall Loss Indication |
| 1999.43 | | 164 | | | | | 235587 | | B/S |
| 2011.61 | | 165 | | | | | 237076 | | B/S |
| 2020.54 | 8.93 | | 0.75 | 23 | 77 | 0.58 | 238149 | 3:30 | Wall Loss Indication |
| 2023.92 | | 166 | | | | | 238555 | | B/S |
| 2035.90 | | 167 | | | | | 239996 | | B/S |
| 2038.25 | 2.35 | | 0.75 | <20 | >80 | >0.6 | 240280 | 9:00 | Wall Loss Indication |
| 2044.14 | 8.24 | | 0.75 | <20 | >80 | >0.6 | 240988 | 3:30 | Wall Loss Indication |
| 2048.01 | | 168 | | | | | 241453 | | B/S |
| 2054.73 | 6.71 | | 0.75 | 21 | 79 | 0.59 | 242261 | 3:30 | Wall Loss Indication - several minor indications |
| 2057.25 | 9.24 | | 0.75 | <20 | >80 | >0.6 | 242564 | 3:30 | Wall Loss Indication |

| Distance from EPA zero feet reference (ft) | Distance from US B&S (ft) | Joint # | Pipe Wall Thickness (inch) | % Loss | % Remaining | Actual Remaining (inch) | Sample number | Channel clock position looking US | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 2059.05 | | 169 | | | | | 242780 | | End of section |

# APPENDIX F:

## AESL Report (58 pp.)

# EPA Trials conducted on a 24Inch Spun Cast Iron Pipeline on Westport Road in Louisville, Kentucky

Report Number RP3042

## DOCUMENT CONTROL

**Client:** Battelle

**Address:** 505 King Avenue
Columbus
Ohio
43201

**Project:** Condition Assessment for EPA Trails

**Report:** EPA Trials conducted on a 24Inch Spun Cast Iron Pipeline or Westport Road in Louisville, Kentucky

**Author(s):** Craig Johnson

**Authorised:** Dick Treece

| Report Issue Status | | | | |
|---|---|---|---|---|
| **Issue** | **Date** | **Description** | **Author(s)** | **Authorised** |
| 01 | 25/09/2009 | First Issue | C Johnson | RJ Treece |
| | | | | |
| | | | | |
| | | | | |

**AUTHOR:** ______________________

**APPROVED:** ______________________

# EXECUTIVE SUMMARY

Advanced Engineering Solutions Limited (AESL) were invited by Battelle, on behalf of the Environmental Protection Agency (EPA), to conduct trials using condition assessment technology that AESL have developed for the assessment of ferrous pipelines. A water utility company in Louisville, Kentucky offered a 24inch cement lined cast iron pipe on which to conduct the demonstrations. The field trails were conducted the week commencing 17th August 2009.

This report is a continuation of the preliminary report, RP2035, and presents the results of the pipeline inspections, a detailed structural / statistical analysis and provides a review of the pipe's condition.

A detailed assessment of the pipe coating and wall condition was conducted at sites F, L and 2.

During the inspection socket and spigot joints were identified throughout the pipeline length.

The pipe internal surface is understood to be lined with cement mortar approximately 5mm in thickness. The pipe's external surface was coated in bitumen paint.

Overall, the wall thickness at the three condition assessment locations was found to range from a minimum of 17.6mm to 20.8mm.

Internal and external defects were identified using the Magnetic Flux Leakage (MFL) External condition assessment tool (ECAT) at all three inspection locations.

Machined defects and threaded holes were found to have been machined into the pipe at site 2. It is understood that the holes were created for connections to be fitted. The connections were required to simulate pipe leakage. The machined defects identified at Site L were analysed in the same manner as the natural defects. Sizes for these defects have been provided.

# CONCLUSIONS

- The pipeline section has been subject to a detailed inspection at 3 locations
- Internal and external corrosion was identified in each location and the depths of defects estimated
- Estimates of ground and traffic loading have been made and combined with the internal pressure to estimate pipeline stresses
- Statistical models of the external defect distributions have been derived and extrapolated over the pipeline length
- Two excavation sites showed similar levels of corrosion with the third site dissimilar and slightly worse
- Soils samples suggested that the soil varied from fairly corrosive to highly corrosive along the route
- The statistical distributions have been extrapolated over the length under consideration and corrosion perforations are predicted to exist if the unexamined lengths are similar to the excavation locations
- Based on the estimated stresses, the defect distribution models, and the assumed pipe material properties defects of sufficient depth to cause structural failure of the pipe may be present.

# CONTENTS

# 1 INTRODUCTION

Advanced Engineering Solutions Limited (AESL) were invited by Battelle, on behalf of the Environmental Protection Agency (EPA), to conduct trials using condition assessment technology that AESL have developed for the assessment of ferrous pipelines. A water utility company in Louisville, Kentucky offered a 24inch cement lined spun cast iron pipe on which to conduct the demonstrations. The field trails were conducted the week commencing 17th August 2009.

# 2 SCOPE OF REPORT

This report is a continuation of the preliminary report, RP2035 and presents the result of the site inspections which includes a description of the pipe installation, wall thickness measurements, and a coating/corrosion inspection for the spun cast iron sections of the pipeline. The results of a detailed statistical analysis have also been provided.

An analysis of the buried pipe section was conducted. This was used to estimate the maximum stress under a minor road load at the pipelines previous operating pressure.

The Appendices include a pipeline schematic including the inspection locations, corrosion grids, Soil Conditions, wall thickness readings, site photographs, confidence intervals and stress analysis results.

# 3 DETAILS OF MAIN

## 3.1 Background Information

For the purpose of the demonstration works a water utility company in Louisville, KY offered a 762m length, 24-inch diameter Delavaud cast iron main. The pipeline was laid in 1933. Joint leaks have been reported between 1973 and 2003 and one pipe leak in September 2008. The pipeline is scheduled to be removed and replaced in September 2009. It is understood that selected sections are to be retrieved for further analysis in the form of destructive inspection. The results from the various inspection technologies will be compared with the destructive measurements.

## 3.2 General

| | |
|---|---|
| Location / Crossing: | Westport Road, Louisville, Kentucky |
| Type: | Minor Road |
| Number of Pipes: | 1 |
| Diameter: | 24-inch |
| Material: | Spun Cast Iron |
| Date Laid: | 1933 |

### 3.3 Hydraulic Profile

| | |
|---|---|
| Duty: | Potable Water |
| Current Operating Pressure: | 3.6 - 4.0bar |
| Possible Test Pressure: | 23.9bar (Taken from BS1211-1945 Class D standard) |
| Supply/Outlet: | Chenwith / Ridgeway |

Pressure data has been provided by Abraham Chen of Battelle.

### 3.4 Site Access

Minor Road: Westport Road

- 10no excavations were accessible during the works. Soil analysis was conducted in all the excavations and condition assessment was conducted in 3no excavations.
- The environment was tested prior to entering the excavation and throughout the condition assessment works.
- Full circumference Magnetic Flux Leakage scans were successfully completed at each of the inspection locations.

## 4 PIPE ASSESSMENT DATA

### 4.1 Installation Details

The 24inch diameter and 762m length spun cast iron pipeline was located below Westport Road, Louisville, Kentucky.

In order to provide input data for structural analysis, information from a pipe manufacturing specification is required. In this case the Client is unable to provide an exact pipe specification and it is AESL practice to use a pattern of wall thickness measurements and date laid to determine the most appropriate pipe specification from available British Standards. The most appropriate standard available is BS1211-1945 Class D. The principal structural details specified by this Standard are given in Table 4.1 below.

| TABLE 4.1 – PRINCIPAL STRUCTURAL DETAILS FOR MAIN BASED ON STANDARD BS1211-1945 CLASS D | |
|---|---|
| Nominal Internal Diameter (Inches) | 24 |
| Nominal Wall Thickness (mm) | 21.6 |
| Maximum Wall Thickness (mm) | 22.6 |
| Minimum Wall Thickness (mm) | 19.8 |
| Design Pressure* (bar) from Standard | 12.0 |
| Specified Minimum UTS (MPa) from Standard | 194 |
| Design Stress** (MPa) from Standard | 48 |

*Design pressure is calculated as 50% of the specified test pressure.
**Design stress is calculated as 25% of the Specified Minimum UTS.

### 4.1.1 Joints

During the inspection socket and spigot joints were identified throughout the pipeline length. 2no. socket and spigot joints were identified at site F and 1no socket and spigot joint was identified at site 2. A socket and spigot joint was identified close to excavation L. AESL were informed that this joint was leaking during the inspection of this site.

### 4.1.2 Pipe Protection

The pipe internal surface is lined with cement mortar approximately 5mm in thickness. This was identified by Battelle upon the removal of pipe sections as shown in Figure 4.1. The pipe's external surface was coated in bitumen paint.

FIGURE 4.1 - PHOTOGRAPH PROVIDED BY BATTELLE OF PIPE CROSS SECTION

### 4.1.3 Ground Conditions

Soil measurements including resistivity, redox, pipe-to-soil potential and pH were taken at every accessible excavation along the length of the pipeline.

Results from the soil survey were used to calculate a score according to the French Standard AFNOR A05-250. This is a recognised method of evaluating the ground corrosiveness to ferrous pipes using parameters such as, nature of the soil, resistivity, moisture content and pH.

The results of the AFNOR score for each excavation has been provided in Table 4.2 below:

TABLE 4.2 – SOIL DATA

| SITE | AFNOR SCORE | NATURE OF GROUND |
|---|---|---|
| SITE 1 | 6 | Fairly Corrosive |
| SITE A | 6 | Fairly Corrosive |
| SITE L | 7 | Fairly Corrosive |
| SITE B | 5 | Fairly Corrosive |
| SITE C | 8 | Highly Corrosive |
| SITE 2 | 5 | Fairly Corrosive |
| SITE D | 6 | Fairly Corrosive |
| SITE E | 6 | Fairly Corrosive |
| SITE F | 9 | Highly Corrosive |
| SITE 3 | 7 | Fairly Corrosive |

The results of the soil properties have been provided in Table A3.1 in appendix 3.

**FIGURE 4.2 - BLACK CONTAMINANTS IN THE GROUND**

Black and green contaminants in the soil were evident within the sidewalls at some of the excavations as seen in Figure 4.2.

## 4.2 Wall Thickness Measurements

The wall thickness was measured using an ultrasound technique while the integrity of the pipe wall was determined by carrying out a series of scans with the External Condition Assessment tool (ECAT).

The tolerance on the ultrasonic instruments is 0.01mm for both the Alphagage (Sonatest Alphagage User Guide, Issue 1) and the Sitescan 140 (Sonatest Sitescan 140 Operators Manual, Issue 4).

10 ultrasonic measurements were taken at every 30-degree pipe orientation. In total 120 ultrasonic measurements were taken at each of the condition assessment locations, sites 2, L and F.

A summary of the results of the ultrasound wall thickness measurements are shown in Table 4.3-4.5 below. A more detailed record of the ultrasound results is provided in Appendix 4.

**TABLE 4.3 – MEASURED WALL THICKNESS RESULTS –SITE F**

| Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | **Overall** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Orientation from TDC (°) | 0 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 | 330 | **0-360** |
| Total Number of Readings | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | **120** |
| Min. Wall Thickness (mm) | 18.4 | 18.5 | 18.1 | 18.0 | 18.4 | 18.0 | 18.6 | 18.8 | 18.5 | 18.4 | 18.6 | 18.6 | **18.0** |
| Max. Wall Thickness (mm) | 19.5 | 19.6 | 19.4 | 19.2 | 20.0 | 19.5 | 19.7 | 20.2 | 20.8 | 20.5 | 19.3 | 19.5 | **20.8** |
| Mean Wall Thickness (mm) | 19.1 | 19.1 | 18.7 | 18.6 | 18.8 | 18.8 | 19.1 | 19.4 | 19.4 | 19.3 | 19.0 | 19.1 | **19.0** |
| Standard deviation | 0.37 | 0.34 | 0.42 | 0.39 | 0.45 | 0.47 | 0.32 | 0.51 | 0.66 | 0.62 | 0.23 | 0.28 | **0.49** |

**TABLE 4.4 – MEASURED WALL THICKNESS RESULTS –SITE 2**

| Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | **Overall** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Orientation from TDC (°) | 0 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 | 330 | **0-360** |
| Total Number of Readings | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | **120** |
| Min. Wall Thickness (mm) | 18.1 | 18.0 | 18.0 | 17.8 | 18.0 | 17.8 | 18.3 | 18.2 | 18.3 | 17.6 | 17.9 | 18.0 | **17.6** |
| Max. Wall Thickness (mm) | 19.3 | 18.7 | 18.9 | 18.8 | 19.2 | 19.5 | 19.2 | 19.3 | 19.3 | 18.8 | 19.2 | 19.0 | **19.5** |
| Mean Wall Thickness (mm) | 18.6 | 18.4 | 18.4 | 18.2 | 18.6 | 18.4 | 18.6 | 18.8 | 18.7 | 18.3 | 18.5 | 18.4 | **18.5** |
| Standard deviation | 0.43 | 0.25 | 0.33 | 0.36 | 0.41 | 0.56 | 0.30 | 0.40 | 0.32 | 0.40 | 0.50 | 0.38 | **0.41** |

**TABLE 4.5 – MEASURED WALL THICKNESS RESULTS –SITE L**

| Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | **Overall** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Orientation from TDC (°) | 0 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 | 330 | **0-360** |
| Total Number of Readings | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | **120** |
| Min. Wall Thickness (mm) | 18.4 | 18.2 | 18.1 | 18.0 | 18.3 | 18.3 | 18.2 | 18.2 | 18.3 | 18.1 | 18.3 | 18.0 | **18.0** |
| Max. Wall Thickness (mm) | 19.1 | 19.5 | 19.2 | 18.9 | 19.0 | 19.2 | 19.1 | 19.2 | 19.4 | 19.2 | 18.9 | 18.7 | **19.5** |
| Mean Wall Thickness (mm) | 18.7 | 18.8 | 18.7 | 18.4 | 18.7 | 18.7 | 18.8 | 18.8 | 19.1 | 18.6 | 18.5 | 18.3 | **18.7** |
| Standard deviation | 0.28 | 0.41 | 0.33 | 0.32 | 0.28 | 0.29 | 0.28 | 0.28 | 0.30 | 0.33 | 0.21 | 0.24 | **0.34** |

Overall, the wall thickness at the three condition assessment locations was found to range from a minimum of 17.6mm to 20.8mm.

## 4.3 Site Assessment

A detailed assessment of the pipeline coating and pipe wall over 1m long lengths was conducted as sites F, L and 2. The location of the sites in relation to each other has been provided in Appendix 1.

The relative soil corrosivity, an inspection of the pipe coating, ultrasound measurements, full circumference ECAT scans to determine the pipe wall condition was conducted at these locations.

Internal and external defects were identified using the ECAT MFL tool at all three inspection locations.

## 4.4 Visual Coating Assessment

A visual coating assessment was carried out in order to identify and assess the integrity of any remaining protective coating on the pipe.

To quantify the level of coating failure present on the pipe, the following model has been created. The pipe's external surface area has been separated into grids and the coating failure identified within these grids reported as a percentage. Each row

(1, 2, 3...n) in the grid is representative of one scanned length of the pipe up to the number of scans completed in total (n) – see Figure 4.3. The results of the coating assessment at site F is detailed in Table 4.6. The results of the coating assessment at sites 2 and L are detailed in Appendix 2 Tables A2.1 and A2.2.

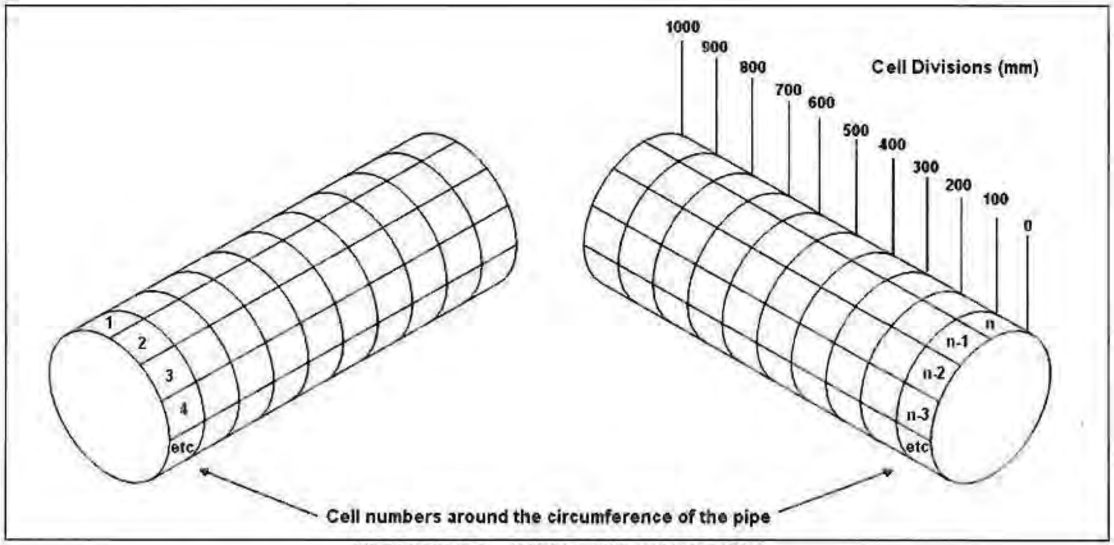
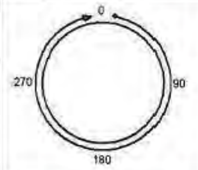


FIGURE 4.3 - PIPE GRID DIAGRAM

**TABLE 4.6 – VISUAL COATING FAILURE DISTRIBUTION – PERCENTAGE COATING FAILURE AT SITE F**

|  | | Axial Distance from Datum Point (mm) | | | | | | | | | | % Coating failure per circumferential location |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0-100 | 100-200 | 200-300 | 300-400 | 400-500 | 500-600 | 600-700 | 700-800 | 800-900 | 900-1000 | |
| Circumferential Orientation (Degrees) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 16 | 5 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 10 | 3 |
| | 33 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 49 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 65 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 82 | 25 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 4 |
| | 98 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 2 |
| | 115 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 131 | 10 | 15 | 10 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| | 147 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 25 | 10 | 15 | 8 |
| | 164 | 0 | 0 | 0 | 0 | 0 | 10 | 30 | 20 | 25 | 50 | 14 |
| | 180 | 0 | 0 | 0 | 0 | 10 | 50 | 50 | 25 | 25 | 70 | 23 |
| | 196 | 0 | 20 | 20 | 0 | 0 | 50 | 50 | 50 | 20 | 75 | 29 |
| | 213 | 0 | 5 | 25 | 20 | 20 | 20 | 50 | 50 | 25 | 40 | 26 |
| | 229 | 25 | 25 | 80 | 80 | 70 | 50 | 25 | 10 | 20 | 0 | 39 |
| | 245 | 25 | 50 | 50 | 25 | 30 | 0 | 5 | 25 | 10 | 0 | 22 |
| | 262 | 25 | 25 | 0 | 0 | 0 | 0 | 25 | 20 | 10 | 0 | 11 |
| | 278 | 0 | 10 | 25 | 0 | 0 | 10 | 50 | 25 | 25 | 25 | 17 |
| | 295 | 25 | 25 | 20 | 5 | 0 | 25 | 75 | 50 | 75 | 25 | 33 |
| | 311 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 327 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 344 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| % Coating failure per axial location | | 7 | 8 | 10 | 6 | 6 | 10 | 18 | 14 | 12 | 15 | |
| Overall area of coating failure (%) | | | | | | | | | | | | 11 |
| Total Cells Analysed | | | | | | | | | | | | 220 |

## 4.5 Condition Assessment

### 4.5.1 Site F

An area of the bitumen paint coating at site F was in poor condition between 170° and 280°.

Approximately 70 localised external pipe wall defects were identified using the ECAT at site F. Further verification of the presence of these external defects was provided by removing the corrosion product in these locations. The largest external defect identified on-site was approximately 6.1mm in depth. After further analysis of the MFL scans from the ECAT, approximately 240 external and 9 internal localised defects were identified at site F.

The pipe's external surface area has been separated into grids similar to Figure 4.3. Using the data collected from the ECAT magnetic inspection corrosion defects have been identified and quantified. The maximum depth of corrosion in each cell in the corrosion grid has been reported and displayed. Therefore where there is more than one defect located in the same cell the smaller of the two will not be displayed. As a large amount of defects were identified at Site F only the largest 20 defects have been chosen to be displayed on the grid in Figure 4.4. Internal and external defects have been distinguished with an "I" and "E" following the defect depth. The defects have been assumed to be hemispherical in shape.

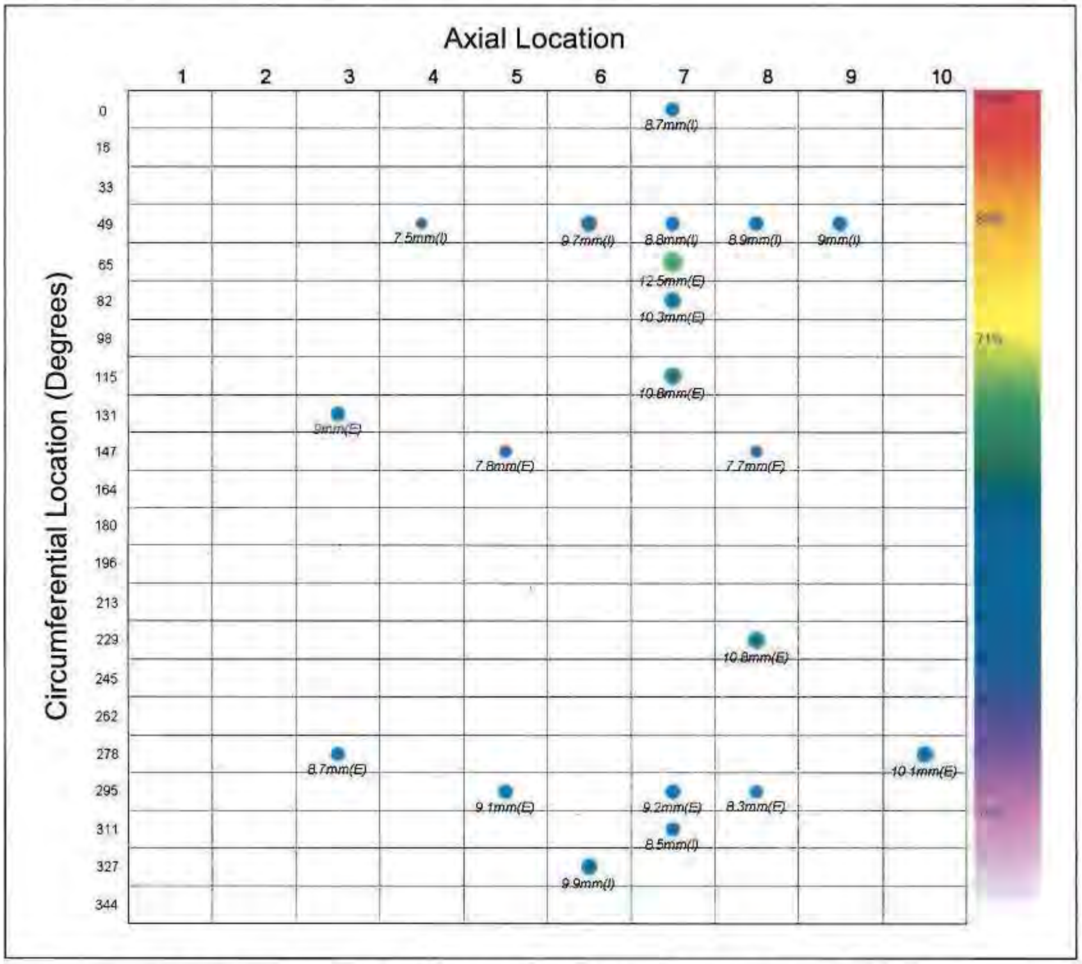


**FIGURE 4.4 – DEFECT PLOT FOR SITE F (20 LARGEST DEFECT DEPTHS)**

Mechanical damage was identified on the pipe between 180° and 270°. Evidence suggests that the mechanical damage had not occurred recently because corrosion was identified within the damaged area as shown in Figure 4.5 below.

FIGURE 4.5 - AREA OF MECHANICAL DAMAGE

Hemispherical machined defects were indicated by the client on an adjacent spool to the one which was scanned by the ECAT at Site F, as shown in Figure 4.6. These defects were scanned and sized for calibration purposes.

FIGURE 4.6 - MACHINED HEMISPHERICAL DEFECTS

### 4.5.2 Site 2

External machined defects with various dimensions were identified in the pipe at Site 2. Because the defects were spread over a pipe length greater than 1m not all the machined defects could be included in a single scanned length. A condition assessment including ECAT scans was performed over a 1m length of the pipe. The machined defects together with the internal and external natural defects included in this scanned length were sized using AESL's algorithms. Analysis of the MFL scans identified approximately 225 localised external defects and 11 localised internal defects at Site 2. Using the data collected from the ECAT magnetic inspection corrosion defects have been identified and quantified. Only the largest 20 defects have been chosen to be displayed on the grid in Figure 4.7.

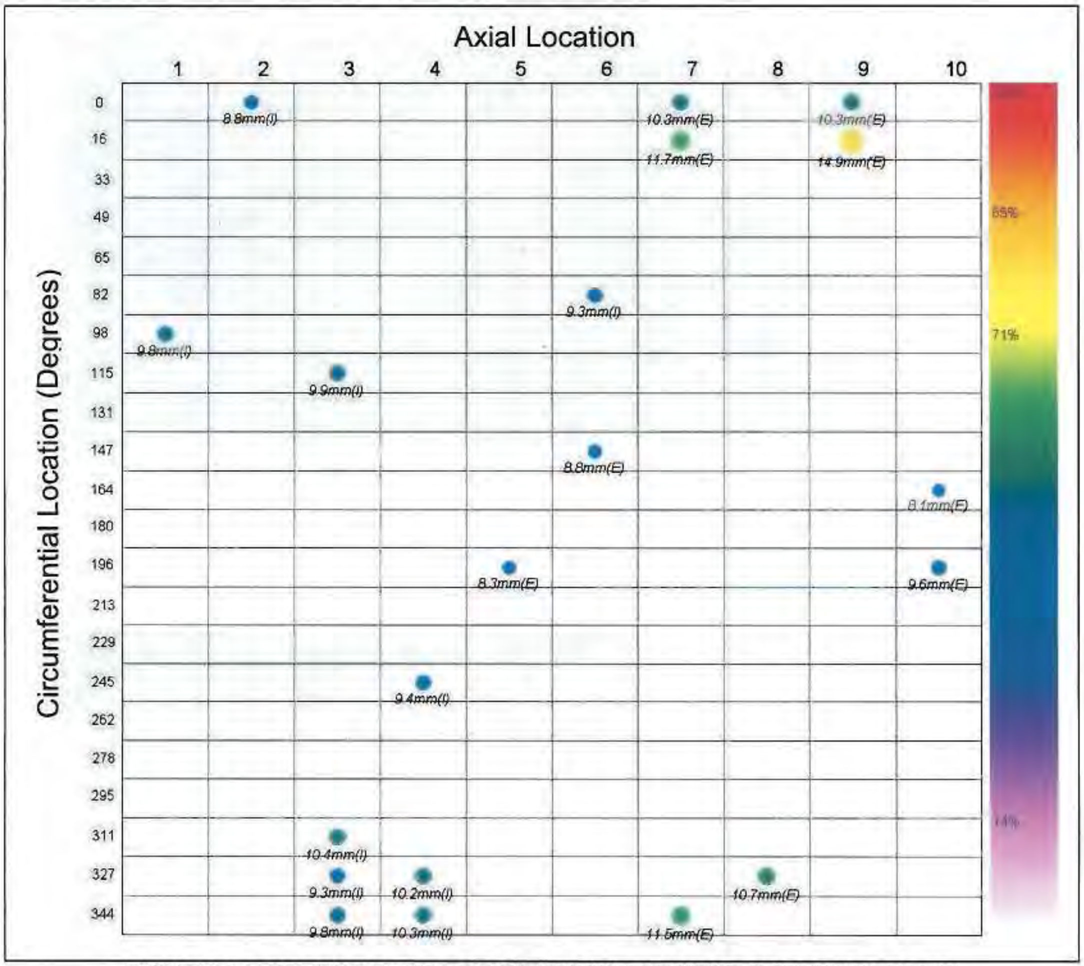


**FIGURE 4.7 DEFECT PLOT FOR SITE 2 (20 LARGEST DEFECT DEPTHS)**

FIGURE 4.8 - EXTERNAL MACHINED DEFECTS

As shown in Figure 4.8, some of the machined defects were located beyond the 1m scanned length. In total, seven machined defects were scanned using the MFL tool.

FIGURE 4.9 - THREADED HOLES

Threaded holes were machined into the pipe between an orientation of 45° and 90° as shown in Figure 4.9 above. These holes were created for connections to be fitted. The connections were required to simulate pipe leakage for other companies who were testing leakage technology the following week. Three through wall threaded holes were within the 1m scanned location during the inspection. The position of the machined defects can be seen on the plot in Figure 4.10.

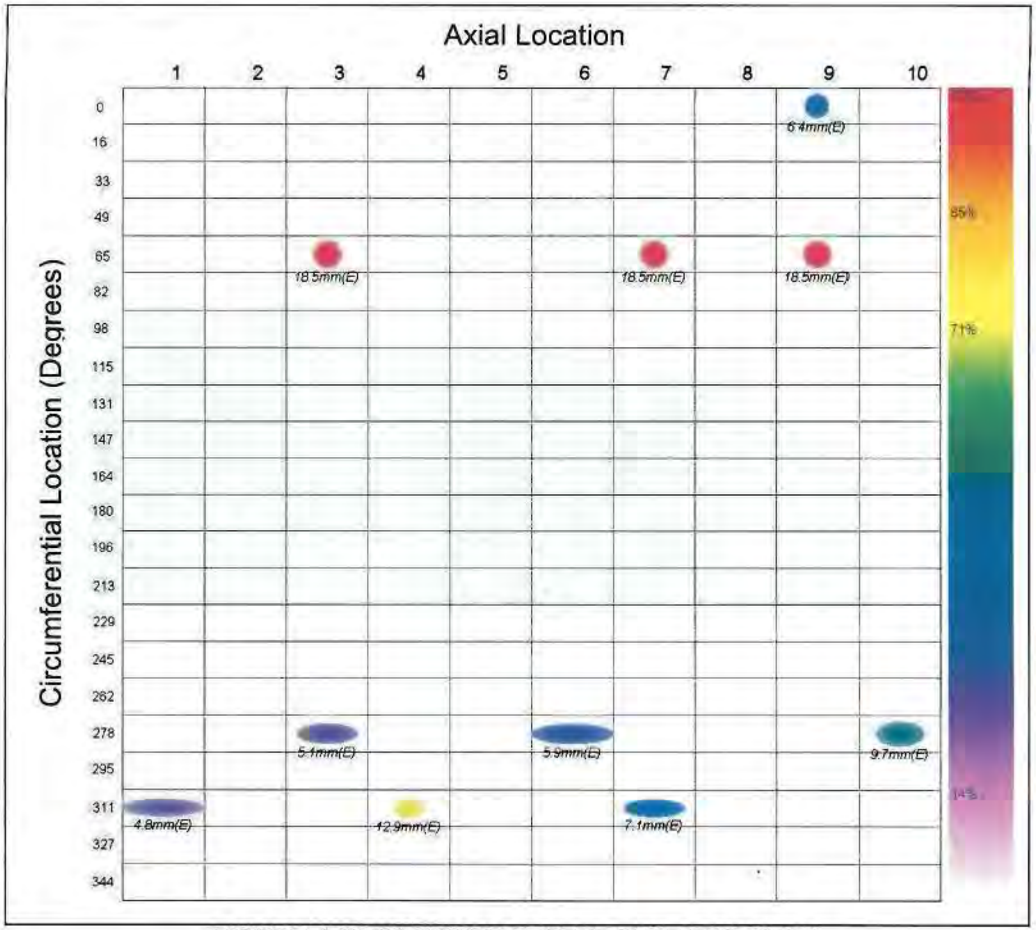


FIGURE 4.10 MACHINED DEFECT PLOT FOR SITE 2

Although, on-site two machined defects were identified at an orientation of approximately 290° (5.9mm external defect) when analysing using AESL algorithms the defects appears as a singular defect as the physical proximity between each defect was too small and the flux leakage output appeared as a singular defect.

The corrosion product within the natural defects was not removed at Site 2 as other companies involved in the trials may have used this location following AESL's departure.

### 4.5.3 Site L

Cracks were identified in the bitumen paint coating at an orientation of 270° as shown in Figure 4.11.

**FIGURE 4.11 - PHOTOGRAPH OF COATING DAMAGE**

Mechanical damage was also identified on the pipeline at approximately 90° and between 180°-280° at this inspection location. External defects were identified in the pipe wall using the MFL tool. Due to the extent of the corrosion some of the external defects could be verified visually without the need to remove corrosion product as shown in Figure 4.12.

**FIGURE 4.12 - PHOTOGRAPH OF EXTERNAL DEFECTS**

Analysis of the MFL scans identified approximately 330 localised external defects and 3 localised internal defects at site L. Using the data collected from the ECAT magnetic inspection corrosion defects have been identified and quantified. As in Site F and 2 a large amount of defects was identified at Site L therefore only the largest 20 defects have been chosen to be displayed on a corrosion grid (Figure 4.13).

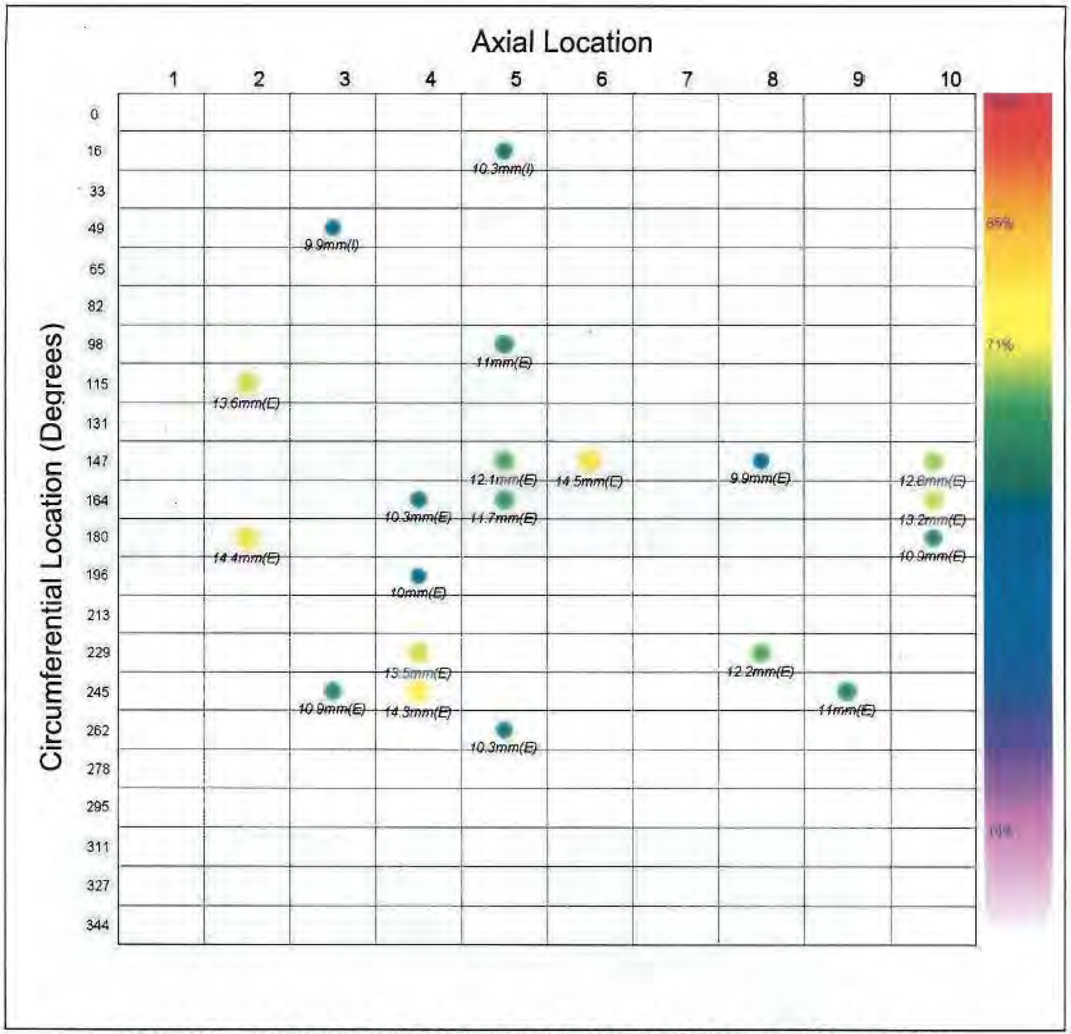


**FIGURE 4.13 DEFECT GRID FOR SITE L (20 LARGEST DEFECT DEPTHS)**

The corrosion product within the natural defects was not removed at Site L as other companies involved in the trials may have used this location following AESL's departure.

## 4.6 Confidence Intervals

The defects presented within the defect grid for Site F has been tabulated below in Table 4.7. Confidence intervals have been calculated for each defect identified. The results for Site 2 and Site L have been included in Appendix 6.

**TABLE 4.7 – CONFIDENCE INTERVAL FOR SITE F**

| ORIENTATION | AXIAL LOCATION | DEFECT SIZE | INTERNAL / EXTERNAL | 95 % CONFIDENCE INTERVAL | |
|---|---|---|---|---|---|
| 65 | 707 | 12.5 | External | 10.9 | 14.3 |
| 115 | 732 | 10.8 | External | 9.5 | 12.2 |
| 229 | 819 | 10.8 | External | 9.5 | 12.2 |
| 82 | 674 | 10.3 | External | 9.1 | 11.6 |
| 278 | 1036 | 10.1 | External | 8.9 | 11.3 |
| 327 | 560 | 9.9 | Internal | 8.8 | 11.0 |
| 49 | 613 | 9.7 | Internal | 8.7 | 10.8 |
| 295 | 672 | 9.2 | External | 8.2 | 10.3 |
| 295 | 463 | 9.1 | External | 8.1 | 10.1 |
| 131 | 274 | 9.0 | External | 8.1 | 10.1 |
| 49 | 906 | 9.0 | Internal | 7.9 | 10.2 |
| 49 | 747 | 8.9 | Internal | 7.9 | 10.1 |
| 49 | 708 | 8.8 | Internal | 7.7 | 10.0 |
| 278 | 292 | 8.7 | External | 7.8 | 9.8 |
| 0 | 652 | 8.7 | Internal | 7.6 | 9.9 |
| 311 | 704 | 8.5 | Internal | 7.4 | 9.8 |
| 295 | 836 | 8.3 | External | 7.4 | 9.3 |
| 147 | 444 | 7.8 | External | 7.0 | 8.7 |
| 147 | 766 | 7.7 | External | 6.9 | 8.6 |
| 49 | 377 | 7.5 | Internal | 6.3 | 8.9 |

# 5 STRUCTURAL ANALYSIS

The following section outlines the stress and defect analysis carried out to evaluate the structural integrity of the main.

## 5.1 Stress Analysis

The stress experienced by the main is a result of both internal and external pressure. The internal pressure is caused by pressurised water flowing through the main. The external pressure is determined by considering the soil overburden and the traffic loading applied to the main at a particular location.

The pipe runs below ground under what is considered to be a minor road. The traffic loading at each inspection location is considered to be minor road loading only.

The maximum operating pressure of the main prior to decommissioning was 4bar (provided by A Cheng of Battelle).

## 5.2 Loading Regimes

### 5.2.1 Soil Overburden Loading

The soil overburden load acting on the pipe was calculated based on the rectangular area directly above the pipe. The measured cover depth was taken to be the distance from the surface to the crown. Assuming a soil density of 2000kgm$^{-3}$, the load due to overburden was thus derived.

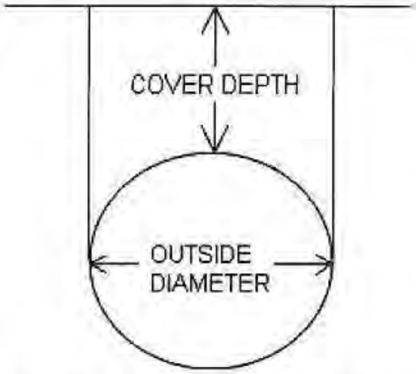


**FIGURE 5.1 - ILLUSTRATES THE VOLUME OF SOIL OVERBURDEN ON THE PIPE**

### 5.2.2 Traffic loading

The average intensity of the traffic load on the pipe due to multiple wheel loads, including impact effects, is calculated from the following equation:

$$w_q = \frac{\Sigma P}{L_1 L_2} \alpha$$

Where:

$w_q$ = Vertical load (pressure on top of pipe) due to surface applied live load

$\Sigma P$ = Sum of individual wheel loads (A maximum axle weight 16.5 tonnes was assumed for a minor road)

$L_1$ = length of the base of the live load distribution

$L_2$ = Width of the base of the live load distribution

$\alpha$ = Live load impact factor

From this equation the pressure on the surface of the pipe was calculated due to the traffic loading (see Table 5.1).

**TABLE 5.1 – INTERNAL PRESSURE AND LOADING**

| Site | Internal Pressure (bar) | Cover depth (m) | Soil overburden loading (Nm^2) | Minor road loading (Nm^2) |
|---|---|---|---|---|
| F | 4 | 1.08 | 21190 | 161865 |
| 2 |  | 1.07 | 20993 |  |
| L |  | 1.73 | 33943 |  |

Note – Any head loss (e.g. due to friction and elevation) is neglected.

## 5.3 Membrane and Bending Stress

Using bending theory, peak stresses in the pipe wall are estimated. It is recognised that these stresses vary around the circumference however only the peak is applied to estimate critical defect sizes. The pipe's circumference was split into six segments to determine the orientation with the maximum stresses. The results of the derived membrane and bending stress for minor road loading at each pipe orientation have been provided in Tables A7.1-A7.3 in Appendix 7. The maximum loads are summarised in the Table 5.2 below.

TABLE 5.2 - SUMMARY OF MAXIMUM LOADS FOR EACH SITE

| SECTION | LOAD CASE | AVERAGE WALL THICKNESS (MM) | MAX MEMBRANE STRESS ($MN/M^2$) | MAX BENDING STRESS ($MN/M^2$) |
|---|---|---|---|---|
| F | Minor Road | 19.0 | 7.0 | 27.1 |
| 2 | Minor Road | 18.5 | 7.2 | 28.8 |
| L | Minor Road | 18.7 | 7.1 | 24.3 |

## 5.4 Analysis of Structural Significance of Corrosion

Internal and external localised corrosion was identified at all the inspection locations. External corrosion ranged from 1.0mm (Site F) to 14.9mm (Site 2) in depth. Internal corrosion ranged from 7.5mm (Site F) to 10.4mm (Site 2).

AESL apply a method based on British Standard 7910 which is based on fracture mechanics theory. A fracture toughness of $10.3MN/m^{3/2}$ for spun cast iron was assumed as a conservative value

Defects which are cracks are likely to give rise to more intense stress fields, and hence smaller predicted critical defect sizes then non planar defects such as corrosion pits. BS 7910 takes a conservative approach to assessing surface flaws due to pitting corrosion, by modelling a pit as a planar flaw of the same depth and shape.

## 5.5 Fracture Mechanics Model

The presence of defects in a pipe wall results in higher stress concentrations in the surrounding area of the pipe wall around the defect and thus, increases the risk of failure.

AESL have developed their own software based on BS 7910:2005, Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures, which allows predictions to be made of the critical depth of a defect that may initiate failure and hence, the acceptability of any defects identified in the inspection.

The software takes into account the properties of the pipe material and the maximum stresses likely to be induced on the main due to the loading regime. Conservative values for the material properties have been estimated from published sources.

Table 5.3 below shows the values used for the Fracture Mechanics Method.

TABLE 5.3 – BS7910 SOFTWARE INPUT DATA

| SECTION | ULTIMATE TENSILE STRENGTH ($MN/M^2$) | YIELD STRENGTH ($MN/M^2$) | TOUGHNESS ($MN/M^{3/2}$) | OUTER DIAMETER (MM) | AVE. WALL THICKNESS (MM) |
|---|---|---|---|---|---|
| F | 194 | 194 | 10.3 | 665 | 19.0 |
| 2 | | | | 665 | 18.5 |
| L | | | | 665 | 18.7 |

The maximum membrane stress and bending stress calculated in Section 5.3 were then applied into the BS7910 software.

Assessment of acceptability of a defect is made by means of a Failure Assessment Diagram (FAD) based on the principles of fracture mechanics. The vertical axis of the FAD is a ratio of the applied conditions to the conditions required to cause brittle fracture; the horizontal axis is the ratio of the applied load to that required to cause plastic collapse. An assessment line, seen as a box in the lower left corner of the plot area in Figure 5.1 below, is also included in the FAD. Calculations for a flaw provide the coordinates for an assessment point. Defects that fall within the assessment lines are considered acceptable.

## 5.6 Results

The analysis showed that a 15.7mm deep defect of hemispherical geometry at Site F would not be acceptable in terms of the risk of structural failure resulting from its presence.

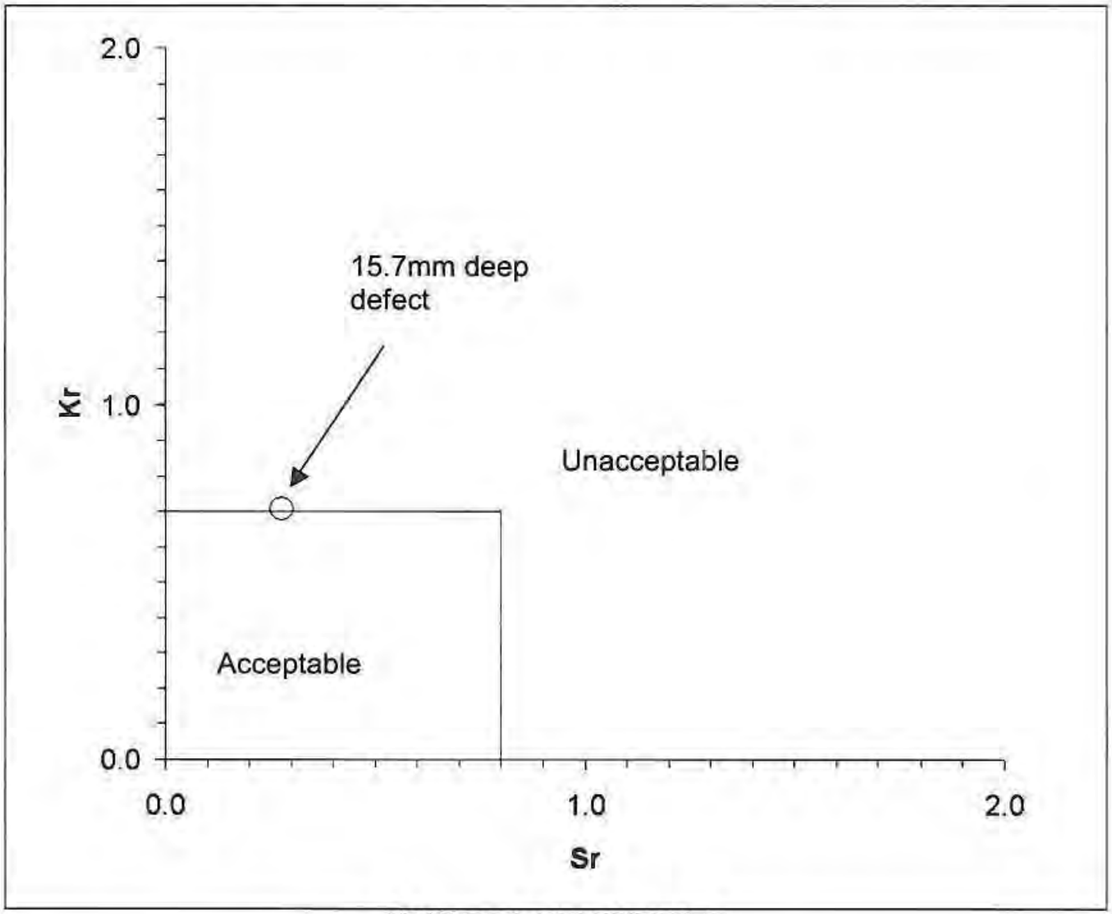


FIGURE 5.1- FAD FOR SITE F

The FAD's for Site 2 and L have been provided in Appendix 8.

Table 5.4 shown below summarises the critical defect depth for each of the Sites.

TABLE 5.4 – DEFECT DEPTH TO CAUSE FRACTURE

| SECTION | LOAD CASE | CRITICAL DEFECT DEPTH AT LOCATION OF MAXIMUM STRESS (MM) |
|---|---|---|
| F | Minor road | 15.7 |
| 2 | Minor road | 14.6 |
| L | Minor road | 17.0 |

It must be noted that this estimation above is based on the presence of one singular defect forming at a point of maximum stress. Defects found in close proximity to each other are likely to give rise to a higher stress concentration and hence further increase the risk of structural failure.

## 5.7 Statistical Analysis of defects

The inspection data from the three sites have been analysed using Extreme Value Theory (EVT) allowing prediction of the size and number of the largest defects, using information from the measured defects. Localised or pitting corrosion are known to follow the Gumbel distribution, from the family of Extreme Value distributions.

The fastest progressing localised corrosion will cause the first perforation. Thus for the phenomena of localised corrosion, an important factor is its maximum values, in this case the depth of the deepest pits.

The Probability ($f_I(x)$) and Cumulative ($F_I(x)$) Equations of the Gumbel distribution are given below where $\alpha$ and $\lambda$ are location and scale parameters respectively:

$$f_I(x) = \frac{1}{\alpha}\exp\left[-\left(-\frac{x-\lambda}{\alpha}\right) - \exp\left\{-\left(\frac{x-\lambda}{\alpha}\right)\right\}\right]$$

$$F_I(x) = \exp\left[-\exp\left\{-\left(\frac{x-\lambda}{\alpha}\right)\right\}\right]$$

The parameter 'x' above represents the population of pits of different depths.

The pipe's external surface area at each inspection site was separated into grids, similar to Figure 4.3 and the deepest single external and internal defect in each grid was identified. The sample of pits was used to produce estimates of the distribution parameters.

External and internal defects need to be analysed separately due to the varying corrosion drivers involved with the two different environments.

### 5.7.1 External Defects

The length of the pipeline has been split into three sections. Each inspection location represents one third of the length of pipeline. By analysing the three sections separately it was shown that Site F and Site 2 were statistically similar however Site L was dissimilar to both F and 2. Therefore, two models were produced one to include Sites F and 2 (represent 2/3 of the pipeline) and the other with Site L (represent 1/3 of the pipeline).

Extreme value distributions have been fitted for the models over a length of 508m (Site F and 2) and 254m (Site L). The distribution parameters used in the above equation are shown in Table 5.5.

**TABLE 5.5 - DISTRIBUTION PARAMETERS**

| SITE | INTERNAL / EXTERNAL | DISTRIBUTION PARAMETERS | MOST LIKELY VALUE | 95% CONFIDENCE LIMITS |
|---|---|---|---|---|
| Site F & 2 | External | Alpha | 1.77858 | 0.261 |
| | | Lambda | 2.98879 | 0.372 |
| Site L | External | Alpha | 2.30153 | 0.345 |
| | | Lambda | 4.34209 | 0.396 |

These distribution parameters have been fitted using the method of maximum likelihood, with the data below 4.5mm left censored. This gives greater emphasis to the deeper defects in the model fit. An example of the illustration of fit is presented in Figure 5.2.

The distribution fits pass Anderson and Darling statistical tests for goodness of fit, adjusted for censored data, at better than the 5% level.

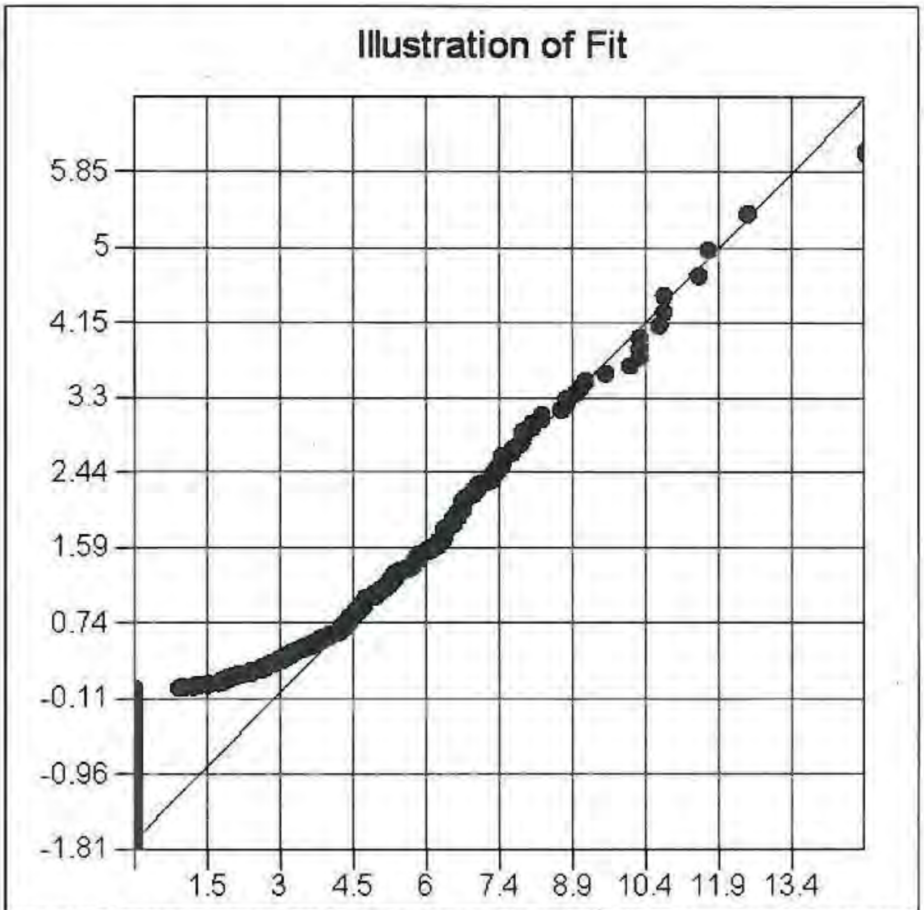


**FIGURE 5.2 – ILLUSTRATION OF FIT FOR PITTING EXTERNAL DEFECTS FOR SITE F & 2**

The results of the statistical analysis are shown in Table 5.6 for the whole pipeline length. 220 cells were inspected at each of the locations.

**TABLE 5.6 – STATISTICAL ANAYSIS RESULTS FOR FULL PIPELINE LENGTH**

| SECTION | INTERNAL / EXTERNAL | APPROXIMATE EXTRAPOLATED LENGTH (M) | AVERAGE WALL THICKNESS (MM) | ESTIMATED DEEPEST PIT (MM) | ESTIMATED NUMBER OF PERFORATIONS ALONG EXTRAPOLATED LENGTH |
|---|---|---|---|---|---|
| Site F & 2 | External | 508 | 18.8 | TW* | 15 |
| Site L | | 254 | 18.7 | TW* | >50 |

*If the deepest defect equals the average wall thickness then it is said to be through wall (TW)

Thus if the pipeline is similar elsewhere to the observed location then it is estimated there is currently a number of through wall external defects along the whole length of the pipeline.

### 5.7.2 Internal defects

Extreme value theory may not be applicable to the internal surface because the pipeline is cement lined and the internal defects probably correspond to the local coating failures. As such surface of the pipeline would not corrode in a way which could be appropriately represented by an extreme value distribution.

A number of internal defects were identified from the scans. The estimated number and sizes of the internal defects located at each of the sites are given in Table 5.7 below:

**TABLE 5.7 – INTERNAL DEFECTS**

| SITE | ORIENTATION (°) | AXIAL LOCATION (MM) | DEFECT SIZE (MM) |
|---|---|---|---|
| F | 327 | 560 | 9.9 |
| | 49 | 613 | 9.7 |
| | 49 | 906 | 9.0 |
| | 49 | 747 | 8.9 |
| | 49 | 708 | 8.8 |
| | 0 | 652 | 8.7 |
| | 311 | 704 | 8.5 |
| | 0 | 701 | 8.2 |
| | 49 | 377 | 7.5 |
| 2 | 311 | 317 | 10.4 |
| | 344 | 404 | 10.3 |
| | 327 | 383 | 10.2 |
| | 344 | 386 | 9.9 |
| | 115 | 245 | 9.9 |
| | 344 | 232 | 9.8 |
| | 98 | 41 | 9.8 |
| | 245 | 384 | 9.4 |
| | 82 | 588 | 9.3 |
| | 327 | 314 | 9.3 |
| | 115 | 205 | 8.8 |
| L | 16 | 522 | 10.3 |
| | 49 | 284 | 9.9 |
| | 33 | 504 | 9.2 |

Note: the table above may not match the defects illustrated in the corrosion grid in section 4 as the grid only displays the maximum internal or external defect in each cell whereas the table above identifies all the internal defects which were estimated with the MFL tool.

# 6 REMAINING LIFE

## 6.1 Perforation

The table below summarises the deepest 5 pits estimated at each location. Similar to Table 5.7, the defects listed in Table 6.1 may not match the defects illustrated in the corrosion grid in section 4 as the grid only displays the maximum defect in each cell whereas the table below identifies all the internal / external defects which were estimated with the MFL tool.

**TABLE 6.1 – DEEPEST DEFECTS**

| SITE | ORIENTATION (°) | AXIAL LOCATION (MM) | EXTERNAL / INTERNAL | DEFECT SIZE (MM) |
|---|---|---|---|---|
| F | 65 | 707 | External | 12.5 |
|  | 115 | 732 | External | 10.8 |
|  | 229 | 819 | External | 10.8 |
|  | 82 | 674 | External | 10.3 |
|  | 278 | 1036 | External | 10.1 |
| 2 | 16 | 854 | External | 14.9 |
|  | 16 | 647 | External | 11.7 |
|  | 344 | 714 | External | 11.5 |
|  | 327 | 785 | External | 10.7 |
|  | 311 | 317 | Internal | 10.4 |
| L | 147 | 561 | External | 14.5 |
|  | 180 | 120 | External | 14.4 |
|  | 245 | 375 | External | 14.3 |
|  | 115 | 110 | External | 13.6 |
|  | 229 | 348 | External | 13.5 |

The statistical models of external defects described in section 5.7.1 suggest that if the remainder of the pipeline is similar in its age and exposure to the examined areas then there are likely to be a number of defects equal to the wall thickness. This would suggest that the life to leakage for this pipeline is minimal.

Iron corrosion product is a matrix of iron and oxides of iron and does have some residual strength. A through wall corrosion defect in iron may remain in situ. Therefore it is possible for through wall corrosion to occur without the presence of a leak.

## 6.2 Critical defects

The table 6.2 summarises the estimated critical defect sizes at which failure of the line may occur, at the points of maximum stress.

The statistical analysis model of external defect distribution has been applied to estimate the likely number of critical defects near highly stresses portion of the pipeline. These numbers are given below:

**TABLE 6.2 – STATISTICAL ANAYSIS FOR MAX STRESS LOCATION FOR FULL PIPELINE LENGTH**

| SECTION | INTERNAL / EXTERNAL | APPROXIMATE EXTRAPOLATED LENGTH (M) | CRITICAL DEFECT DEPTH (MM) | ESTIMATED DEEPEST PIT (MM) | ESTIMATED NUMBER OF CRITICAL DEFECTS WITHIN EXTRAPOLATED LENGTH |
|---|---|---|---|---|---|
| Site F & 2 | External | 508 | 14.6 | 14.6 | 13 |
| Site L |  | 254 | 17 | 17 | >50 |

Extreme value analysis has been conducted on the highly stressed portion of pipeline to estimate the number of critical defects along the pipeline length. The statistical analysis model estimates that more than 60 critical defects may be present along the pipeline length.

Based on the estimated maximum stresses, the defect distribution models, and the assumed pipe material properties defects of sufficient depth to cause structural failure of the pipe may be present.

## 7 DISCUSSION

Advanced Engineering Solutions Limited (AESL) were invited by Battelle, on behalf of the Environmental Protection Agency (EPA), to conduct trials using condition assessment technology that AESL have developed for the assessment of ferrous pipelines. A water utility company in Louisville, Kentucky offered a 24inch cement lined cast iron pipe on which to conduct the demonstrations. The field trails were conducted the week commencing 17th August 2009.

During the inspection socket and spigot joints were identified throughout the pipeline length.

A detailed assessment of the pipe coating and wall condition was conducted at sites F, L and 2.

Soil measurements including resistivity, redox, pipe-to-soil potential and pH were taken at every accessible excavation along the length of the pipeline. Soil samples were given to Battelle to determine the moisture content. The soil samples were classified as being corrosive to highly corrosive in areas.

Internal and external defects were identified using the Magnetic Flux Leakage (MFL) External condition assessment tool (ECAT) at all three inspection locations. Extensive external defects were identified at each of the three sites inspected. A minimal amount of internal defects were identified which could suggest that the lining had broken down in localised areas.

Machined defects were indicated by the client in a pipe spool adjacent to the spool at site F and in the spool examined at site 2. Both these areas were scanned using the MFL tool. The machined defects identified at Site L were analysed in the same manner as the natural defects. Sizes for these defects have been provided.

Threaded holes were found to have been machined into the pipe at site 2. It is understood that these holes were created for connections to be fitted. The connections were required to simulate pipe leakage.

Statistical analysis predicts that greater than 65 through wall defects would be present along the pipeline length. Also, greater than 60 critical defects have been predicted to be present in the highly stressed locations of the pipeline.

### 7.1 Issues & Future improvements

Material properties were not provided by the client and therefore have to be taken from the most suitable standard available. As there are uncertainties of the material properties this will cause uncertainties in the stress analysis and the subsequent critical defect depths predicted. The identification of historic American standards for Cast Iron pipe would enable more appropriate assessment of original dimensions, material properties and test pressures.

As well as the material properties being dissimilar, there may also be variations in the soil properties and hence the corrosion driver along the pipeline length. This may affect the validity of the statistical extrapolation process. The soil samples which were analysed provide a snapshot of the soil properties only. These properties may vary depending on climate conditions.

AESL sizing software is based on calibration scans of flat-bottomed corrosion defects, with different pipes of different wall thicknesses, and potentially different magnetic properties. ASEL realise that natural defect's shape and actual depth is more complex and recognise that further work is required to replicate this.

The fracture mechanics software designed from BS7910 models defects as a planer cracks. This is a conservative approach to fracture mechanics. Stress varies around circumference of the pipeline, the maximum stress usually being located around the pipe spring level or top and bottom dead centre. Critical defects, which are estimated using the software, are based on a singular defect being present at a point of maximum stress. Defects found in close proximity to each other are likely to give rise to a higher stress concentration and hence further increase the risk of structural failure.

AESL uses both UK and Australian traffic loading models. It would be more appropriate to apply local standards for the derivation of traffic loads.

## 8 CONCLUSIONS

- The pipeline section has been subject to a detailed inspection at 3 locations
- Internal and external corrosion was identified in each location and the depths of defects estimated
- Estimates of ground and traffic loading have been made and combined with the internal pressure to estimate pipeline stresses
- Statistical models of the external defect distributions have been derived and extrapolated over the pipeline length
- Two excavation sites showed similar levels of corrosion (Site F & 2) with the third site dissimilar and slightly worse (Site L)
- Soils samples suggested that the soil varied from fairly corrosive to highly corrosive along the route
- The statistical distributions have been extrapolated over the length under consideration and corrosion perforations are predicted to exist if the unexamined lengths are similar to the excavation locations
- Based on the estimated stresses, the defect distribution models, and the assumed pipe material properties defects of sufficient depth to cause structural failure of the pipe may be present.

# Appendix 1 Site Locations

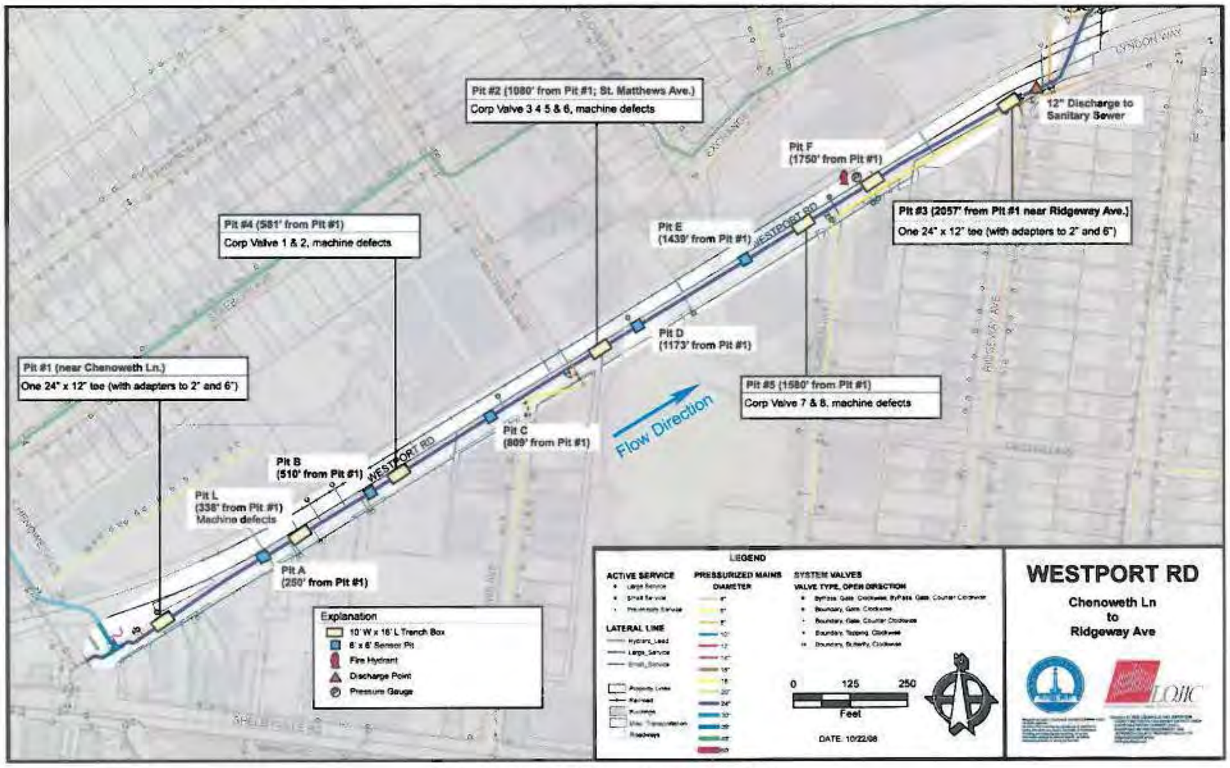


FIGURE A1.1 INSPECTION LOCATIONS

# Appendix 2 Coating Grid

**TABLE A2.1 VISUAL COATING FAILURE DISTRIBUTION – PERCENTAGE COATING FAILURE SITE 2**

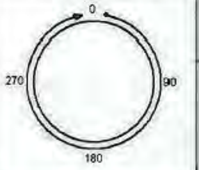
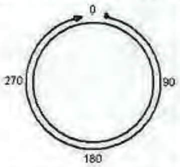
|  |  | Axial Distance from Datum Point (mm) |  |  |  |  |  |  |  |  |  | % Coating failure per circumferential location |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | 0-100 | 100-200 | 200-300 | 300-400 | 400-500 | 500-600 | 600-700 | 700-800 | 800-900 | 900-1000 |  |
| Circumferential Orientation (Degrees) | 0 | 50 | 40 | 20 | 10 | 20 | 40 | 60 | 30 | 20 | 10 | 30 |
|  | 16 | 10 | 15 | 10 | 20 | 25 | 75 | 90 | 100 | 50 | 20 | 42 |
|  | 33 | 40 | 25 | 30 | 50 | 50 | 75 | 80 | 100 | 30 | 25 | 51 |
|  | 49 | 50 | 20 | 40 | 20 | 75 | 80 | 100 | 100 | 75 | 20 | 58 |
|  | 65 | 25 | 25 | 15 | 40 | 70 | 90 | 100 | 100 | 100 | 70 | 64 |
|  | 82 | 5 | 5 | 20 | 50 | 75 | 75 | 90 | 100 | 100 | 75 | 60 |
|  | 98 | 25 | 20 | 20 | 50 | 100 | 100 | 100 | 100 | 100 | 80 | 70 |
|  | 115 | 100 | 80 | 80 | 80 | 100 | 80 | 100 | 100 | 100 | 100 | 92 |
|  | 131 | 100 | 100 | 90 | 80 | 80 | 80 | 100 | 100 | 100 | 100 | 93 |
|  | 147 | 100 | 90 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 |
|  | 164 | 90 | 90 | 80 | 90 | 80 | 80 | 100 | 100 | 100 | 100 | 91 |
|  | 180 | 100 | 100 | 100 | 100 | 100 | 90 | 100 | 100 | 100 | 100 | 99 |
|  | 196 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
|  | 213 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
|  | 229 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
|  | 245 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
|  | 262 | 40 | 70 | 75 | 75 | 80 | 50 | 70 | 100 | 100 | 100 | 76 |
|  | 278 | 50 | 70 | 20 | 70 | 90 | 75 | 80 | 90 | 50 | 70 | 67 |
|  | 295 | 10 | 10 | 20 | 25 | 40 | 50 | 100 | 100 | 75 | 75 | 51 |
|  | 311 | 5 | 10 | 5 | 20 | 25 | 40 | 80 | 70 | 70 | 70 | 40 |
|  | 327 | 20 | 10 | 5 | 5 | 10 | 20 | 25 | 25 | 75 | 75 | 27 |
|  | 344 | 10 | 10 | 15 | 20 | 25 | 25 | 80 | 80 | 70 | 20 | 36 |
| % Coating failure per axial location |  | 56 | 54 | 52 | 59 | 70 | 74 | 89 | 91 | 83 | 73 |  |
| Overall area of coating failure (%) |  |  |  |  |  |  |  |  |  |  |  | 70 |
| Total Cells Analysed |  |  |  |  |  |  |  |  |  |  |  | **220** |

**TABLE A2.2 VISUAL COATING FAILURE DISTRIBUTION – PERCENTAGE COATING FAILURE SITE L**

|  | | Axial Distance from Datum Point (mm) | | | | | | | | | | % Coating failure per circumferential location |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0-100 | 100-200 | 200-300 | 300-400 | 400-500 | 500-600 | 600-700 | 700-800 | 800-900 | 900-1000 | |
| Circumferential Orientation (Degrees) | 0 | 20 | 20 | 10 | 5 | 15 | 5 | 25 | 40 | 15 | 10 | 17 |
| | 16 | 5 | 5 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 2 |
| | 33 | 0 | 5 | 5 | 0 | 0 | 0 | 10 | 5 | 5 | 0 | 3 |
| | 49 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 0 | 5 | 2 |
| | 65 | 0 | 10 | 0 | 10 | 5 | 5 | 0 | 0 | 0 | 0 | 3 |
| | 82 | 0 | 0 | 10 | 0 | 15 | 5 | 5 | 10 | 20 | 5 | 7 |
| | 98 | 5 | 20 | 5 | 0 | 5 | 0 | 5 | 0 | 0 | 10 | 5 |
| | 115 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 1 |
| | 131 | 0 | 10 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 2 |
| | 147 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 1 |
| | 164 | 0 | 0 | 0 | 0 | 10 | 0 | 5 | 0 | 0 | 10 | 3 |
| | 180 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 20 | 3 |
| | 196 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 213 | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 0 | 0 | 0 | 2 |
| | 229 | 0 | 0 | 10 | 20 | 25 | 0 | 0 | 0 | 0 | 0 | 6 |
| | 245 | 25 | 15 | 20 | 10 | 10 | 0 | 10 | 0 | 5 | 0 | 10 |
| | 262 | 50 | 25 | 40 | 50 | 25 | 25 | 15 | 20 | 15 | 0 | 27 |
| | 278 | 15 | 15 | 20 | 20 | 25 | 40 | 40 | 60 | 50 | 25 | 31 |
| | 295 | 0 | 5 | 0 | 0 | 0 | 0 | 10 | 20 | 0 | 0 | 4 |
| | 311 | 0 | 5 | 0 | 0 | 0 | 0 | 5 | 0 | 15 | 20 | 5 |
| | 327 | 0 | 0 | 0 | 0 | 5 | 0 | 5 | 5 | 10 | 0 | 3 |
| | 344 | 5 | 0 | 5 | 5 | 0 | 0 | 5 | 0 | 0 | 0 | 2 |
| % Coating failure per axial location | | 6 | 6 | 6 | 5 | 8 | 4 | 7 | 8 | 7 | 5 | |
| Overall area of coating failure (%) | | | | | | | | | | | | 6 |
| Total Cells Analysed | | | | | | | | | | | | **220** |

# Appendix 3 Soil Conditions

**TABLE A3.1 – SOIL DATA**

| | pH | Pipe to Soil | Redox | Depth to Crown | Resistivity | Moisture | Moisture Content | Description of Soil | Ease of Removal | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| **SITE 1** | 8.50 | -587 | 160 | 1210 | 2669 | Moist | 25.5 | Clay and stony with traces of green and black colours | Stiff | Storm drain was located in the excavation. Storm drain was cut open for the excavation. Water was pumped out prior to soil analysis. |
| **SITE A** | 7.30 | -561 | 77 | 1290 | 2450 | Walls: Moist<br>Bed: Saturated | 24.2 | Clay | Stiff | |
| **SITE L** | 7.25 | -601 | 218 | 1730 | 1206 | Sidewalls: Moist<br>bed: saturated | 23.5 | Clay | Sidewall: stiff<br>Bedding: Loose | Leak was located at a joint close to the inspection location. Excavation was pumped prior and during the inspection works. |
| **SITE B** | 7.50 | -518 | 119 | 1200 | 4230 | Moist | 26.6 | Sandy Clay with traces of black | Stiff | |
| **SITE C** | 6.50 | -614 | 148 | 1050 | 817 | Dry / Moist | 23.1 | Sandy Clay with traces of black | Stiff | |
| **SITE 2** | 7.25 | -615 | 110 | 1070 | 2400 | Moist | 22.8 | Clay with traces of black | Stiff / Firm | |
| **SITE D** | 7.00 | -557 | 141 | 1300 | 1436 | Dry | 23.5 | Clay sandy with traces of black | Stiff | |
| **SITE E** | 7.80 | -649 | 123 | 1300 | 1198 | Dry | 27.9 | Sandy clay with stones. Black and brown in colour | Stiff | Bitumen from road surface seeping through the soil |
| **SITE F** | 6.25 | -645 | 101 | 1080 | 637 | Moist | 24.3 | Dense Clay | Firm | |
| **SITE 3** | 6.00 | -691 | 120 | 1130 | 1631 | Moist | 28.9 | Clay and stony | Stiff | Started to rain heavily during test. Surface was saturated with rain water. Below the surface the ground was Moist/dry. Soil in excavation wall is compacted |

# Appendix 4 Wall Thickness Measurements

**TABLE A4.1 – MEASURED WALL THICKNESS RESULTS – SITE F**

| | Orientation from TDC (°) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | 0 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 | 330 |
| 1 | 19.3 | 19.5 | 19.5 | 19.5 | 19.2 | 19.3 | 18.8 | 19.1 | 18.8 | 18.4 | 19.3 | 19.5 |
| 2 | 19.6 | 19.4 | 19.3 | 19.1 | 19.2 | 19.1 | 18.9 | 18.8 | 18.7 | 18.5 | 19.6 | 19.4 |
| 3 | 19.0 | 19.1 | 19.4 | 18.9 | 18.7 | 18.8 | 18.7 | 18.3 | 18.1 | 18.2 | 19.0 | 19.1 |
| 4 | 18.8 | 19.2 | 19.0 | 18.7 | 18.6 | 18.7 | 18.7 | 18.1 | 18.0 | 18.2 | 18.8 | 19.2 |
| 5 | 18.8 | 18.9 | 18.8 | 18.9 | 20.0 | 18.6 | 18.6 | 18.5 | 18.7 | 18.4 | 18.8 | 18.9 |
| 6 | 18.9 | 18.7 | 19.1 | 18.7 | 19.2 | 19.1 | 19.5 | 19.0 | 18.0 | 18.1 | 18.9 | 18.7 |
| 7 | 19.4 | 19.3 | 18.9 | 19.0 | 18.9 | 18.8 | 19.7 | 19.2 | 19.0 | 18.6 | 19.4 | 19.3 |
| 8 | 20.1 | 19.5 | 19.0 | 19.6 | 19.9 | 20.2 | 18.9 | 19.3 | 18.8 | 19.0 | 20.1 | 19.5 |
| 9 | 19.3 | 19.9 | 20.8 | 18.8 | 19.7 | 18.8 | 19.2 | 19.4 | 19.1 | 18.5 | 19.3 | 19.9 |
| 10 | 19.0 | 20.1 | 20.5 | 19.6 | 19.2 | 19.0 | 18.9 | 19.6 | 19.0 | 18.4 | 19.0 | 20.1 |

**TABLE A4.2 – MEASURED WALL THICKNESS RESULTS – SITE 2**

| | Orientation from TDC (°) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | 0 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 | 330 |
| 1 | 18.7 | 18.4 | 18.1 | 18.1 | 18.5 | 18.3 | 19.3 | 19.1 | 18.8 | 19.1 | 18.7 | 18.4 |
| 2 | 18.6 | 18.4 | 18.1 | 18.0 | 18.0 | 18.3 | 18.6 | 18.5 | 18.7 | 18.3 | 18.6 | 18.4 |
| 3 | 18.6 | 18.0 | 18.1 | 18.5 | 18.7 | 18.8 | 18.9 | 18.0 | 18.3 | 18.2 | 18.6 | 18.0 |
| 4 | 18.0 | 18.0 | 18.0 | 17.8 | 17.9 | 18.7 | 18.6 | 18.8 | 18.3 | 18.3 | 18.0 | 18.0 |
| 5 | 18.1 | 18.4 | 18.4 | 18.0 | 18.9 | 18.9 | 18.2 | 18.9 | 19.2 | 18.8 | 18.1 | 18.4 |
| 6 | 19.2 | 18.3 | 18.0 | 18.5 | 18.1 | 17.9 | 17.8 | 18.2 | 18.3 | 19.5 | 19.2 | 18.3 |
| 7 | 19.2 | 19.1 | 18.5 | 18.5 | 18.4 | 18.7 | 18.5 | 18.4 | 18.3 | 18.6 | 19.2 | 19.1 |
| 8 | 19.2 | 18.5 | 18.6 | 19.0 | 19.2 | 18.3 | 19.3 | 18.8 | 18.5 | 18.2 | 19.2 | 18.5 |
| 9 | 18.8 | 18.6 | 18.4 | 18.5 | 18.7 | 18.3 | 18.6 | 18.7 | 19.2 | 19.3 | 18.8 | 18.6 |
| 10 | 18.2 | 18.3 | 18.8 | 17.8 | 17.6 | 18.1 | 18.2 | 18.6 | 18.5 | 18.8 | 18.2 | 18.3 |

**TABLE A4.3 – MEASURED WALL THICKNESS RESULTS – SITE L**

| | Orientation from TDC (°) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | 0 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 | 330 |
| 1 | 19.1 | 19.0 | 19.0 | 19.0 | 18.5 | 18.4 | 18.4 | 18.7 | 18.6 | 18.5 | 19.1 | 19.0 |
| 2 | 19.3 | 19.5 | 18.9 | 18.7 | 18.9 | 18.3 | 18.2 | 18.5 | 18.7 | 19.0 | 19.3 | 19.5 |
| 3 | 19.2 | 18.8 | 18.9 | 18.7 | 18.6 | 18.2 | 18.1 | 18.9 | 18.9 | 18.7 | 19.2 | 18.8 |
| 4 | 18.9 | 18.1 | 18.7 | 18.6 | 18.6 | 18.2 | 18.1 | 18.0 | 18.0 | 18.4 | 18.9 | 18.1 |
| 5 | 19.0 | 19.0 | 19.0 | 18.6 | 18.8 | 18.8 | 18.6 | 18.3 | 18.4 | 18.3 | 19.0 | 19.0 |
| 6 | 19.2 | 19.0 | 19.0 | 18.7 | 18.5 | 18.3 | 18.5 | 18.5 | 18.7 | 18.9 | 19.2 | 19.0 |
| 7 | 19.1 | 18.9 | 18.7 | 19.1 | 18.7 | 19.0 | 18.8 | 18.8 | 18.2 | 18.5 | 19.1 | 18.9 |
| 8 | 18.9 | 19.2 | 18.9 | 18.8 | 18.8 | 18.6 | 19.0 | 18.7 | 18.2 | 18.5 | 18.9 | 19.2 |
| 9 | 19.2 | 19.4 | 19.2 | 19.3 | 19.1 | 19.0 | 18.3 | 19.1 | 19.1 | 18.9 | 19.2 | 19.4 |
| 10 | 19.0 | 19.2 | 18.8 | 18.6 | 18.5 | 18.1 | 18.4 | 18.6 | 18.5 | 18.3 | 19.0 | 19.2 |

# Appendix 5 Site Photographs

## Site F

FIGURE A5.1 - PHOTOGRAPH OF EXCAVATION LOCATION

FIGURE A5.2 - PHOTOGRAPH OF PIPE IN EXCAVATION

**FIGURE A5.3 - PHOTOGRAPH OF COATING / CORROSION GRID**

**FIGURE A5.4 - PHOTOGRAPH OF MFL TOOL ON THE PIPE**

FIGURE A5.5 - PHOTOGRAPH OF MECHANICAL DAMAGE AND CORROSION

## Site 2

FIGURE A5.6 - PHOTOGRAPH OF EXCAVATION LOCATION

FIGURE A5.7 - PHOTOGRAPH OF COATING / CORROSION GRID

FIGURE A5.8 - PHOTOGRAPH OF MFL TOOL ON THE PIPE

FIGURE A5.9 - PHOTOGRAPH OF MACHINED DEFECTS IN THE PIPE

**FIGURE A5.10 - PHOTOGRAPH OF MACHINED THREADED HOLES IN THE PIPE**

## Site L

FIGURE A5.11 - PHOTOGRAPH OF EXCAVATION LOCATION

FIGURE A5.12 - PHOTOGRAPH OF PIPE IN EXCAVATION

FIGURE A5.13 - PHOTOGRAPH OF COATING / CORROSION GRID

FIGURE A5.14 - PHOTOGRAPH OF MFL TOOL ON THE PIPE

FIGURE A5.15 - PHOTOGRAPH OF DEFECTS IDENTIFIED ON THE PIPE

FIGURE A5.16 - PHOTOGRAPH OF COATING DEFECTS

FIGURE A5.17 - PHOTOGRAPH OF MECHANICAL DAMAGE TO THE PIPE

# Appendix 6 Confidence Intervals

**TABLE A6.1 – CONFIDENCE INTERVAL FOR SITE 2**

| ORIENTATION | AXIAL LOCATION | DEFECT SIZE | INTERNAL / EXTERNAL | 95 % CONFIDENCE INTERVAL | |
|---|---|---|---|---|---|
| 16 | 853 | 14.9 | External | 12.7 | 17.5 |
| 16 | 646 | 11.7 | External | 10.2 | 13.4 |
| 344 | 714 | 11.5 | External | 10.1 | 13.2 |
| 327 | 785 | 10.7 | External | 9.4 | 12.2 |
| 311 | 316 | 10.4 | Internal | 9.4 | 11.5 |
| 0 | 691 | 10.3 | External | 9.1 | 11.7 |
| 344 | 403 | 10.3 | Internal | 9.3 | 11.4 |
| 0 | 953 | 10.3 | External | 9.0 | 11.6 |
| 327 | 383 | 10.2 | Internal | 9.2 | 11.4 |
| 115 | 245 | 9.9 | Internal | 8.9 | 11.0 |
| 344 | 232 | 9.8 | Internal | 8.8 | 10.9 |
| 98 | 40 | 9.8 | Internal | 8.7 | 10.9 |
| 196 | 1042 | 9.6 | External | 8.5 | 10.8 |
| 245 | 384 | 9.4 | Internal | 8.4 | 10.5 |
| 82 | 587 | 9.3 | Internal | 8.3 | 10.5 |
| 327 | 314 | 9.3 | Internal | 8.2 | 10.4 |
| 0 | 651 | 8.8 | External | 7.8 | 9.9 |
| 147 | 628 | 8.8 | External | 7.8 | 9.9 |
| 196 | 205 | 8.3 | Internal | 7.7 | 9.9 |
| 164 | 456 | 8.1 | External | 7.4 | 9.3 |

**TABLE A6.2 – CONFIDENCE INTERVAL FOR SITE L**

| ORIENTATION | AXIAL LOCATION | DEFECT SIZE | INTERNAL / EXTERNAL | 95 % CONFIDENCE INTERVAL | |
|---|---|---|---|---|---|
| 147 | 561 | 14.5 | External | 12.4 | 17.0 |
| 180 | 121 | 14.4 | External | 12.3 | 16.8 |
| 245 | 376 | 14.3 | External | 12.3 | 16.7 |
| 115 | 110 | 13.6 | External | 11.7 | 15.7 |
| 229 | 348 | 13.5 | External | 11.7 | 15.7 |
| 164 | 931 | 13.2 | External | 11.4 | 15.3 |
| 147 | 1044 | 12.8 | External | 11.1 | 14.8 |
| 229 | 828 | 12.2 | External | 10.6 | 14.0 |
| 147 | 477 | 12.1 | External | 10.5 | 13.9 |
| 164 | 480 | 11.7 | External | 10.2 | 13.4 |
| 245 | 948 | 11.0 | External | 9.7 | 12.5 |
| 98 | 500 | 11.0 | External | 9.6 | 12.5 |
| 180 | 986 | 10.9 | External | 9.5 | 12.3 |
| 245 | 225 | 10.9 | External | 9.5 | 12.3 |
| 262 | 449 | 10.3 | External | 9.1 | 11.7 |
| 16 | 504 | 10.3 | Internal | 9.3 | 11.4 |
| 164 | 361 | 10.3 | External | 9.1 | 11.6 |
| 196 | 422 | 10.0 | External | 8.8 | 11.3 |
| 147 | 842 | 9.9 | External | 8.8 | 11.2 |
| 49 | 283 | 9.9 | Internal | 8.9 | 11.0 |

# Appendix 7 Stress Analysis Results

**TABLE A7.1–MEMBRANE AND BENDING STRESS PIPELINE SITE F**

| Circumferential position (degrees) | Stress | Minor road loading |
|---|---|---|
| 0 to 15 | Membrane Stress (MPa) | 7.0 |
| | Bending Stress (MPa) | 27.1 |
| 15 to 30 | Membrane Stress (MPa) | 6.9 |
| | Bending Stress (MPa) | 23.5 |
| 30 to 45 | Membrane Stress (MPa) | 6.8 |
| | Bending Stress (MPa) | 13.5 |
| 45 to 60 | Membrane Stress (MPa) | 6.3 |
| | Bending Stress (MPa) | 9.3 |
| 60 to 75 | Membrane Stress (MPa) | 6.1 |
| | Bending Stress (MPa) | 20.8 |
| 75 to 90 | Membrane Stress (MPa) | 6.0 |
| | Bending Stress (MPa) | 26.7 |

**TABLE A7.2 –MEMBRANE AND BENDING STRESS PIPELINE SITE 2**

| Circumferential position (degrees) | Stress | Minor road Loading |
|---|---|---|
| 0 to 15 | Membrane Stress (MPa) | 7.2 |
| | Bending Stress (MPa) | 28.8 |
| 15 to 30 | Membrane Stress (MPa) | 7.1 |
| | Bending Stress (MPa) | 24.9 |
| 30 to 45 | Membrane Stress (MPa) | 6.9 |
| | Bending Stress (MPa) | 14.4 |
| 45 to 60 | Membrane Stress (MPa) | 6.5 |
| | Bending Stress (MPa) | 9.8 |
| 60 to 75 | Membrane Stress (MPa) | 6.3 |
| | Bending Stress (MPa) | 22.0 |
| 75 to 90 | Membrane Stress (MPa) | 6.1 |
| | Bending Stress (MPa) | 28.3 |

**TABLE A7.3 –MEMBRANE AND BENDING STRESS PIPELINE SITE L**

| Circumferential position (degrees) | Stress | Minor road loading |
|---|---|---|
| 0 to 15 | Membrane Stress (MPa) | 7.1 |
| | Bending Stress (MPa) | 24.3 |
| 15 to 30 | Membrane Stress (MPa) | 7.1 |
| | Bending Stress (MPa) | 21.1 |
| 30 to 45 | Membrane Stress (MPa) | 6.9 |
| | Bending Stress (MPa) | 12.2 |
| 45 to 60 | Membrane Stress (MPa) | 6.5 |
| | Bending Stress (MPa) | 8.3 |
| 60 to 75 | Membrane Stress (MPa) | 6.3 |
| | Bending Stress (MPa) | 18.6 |
| 75 to 90 | Membrane Stress (MPa) | 6.2 |
| | Bending Stress (MPa) | 24.0 |

# Appendix 8 Failure Assessment Diagrams

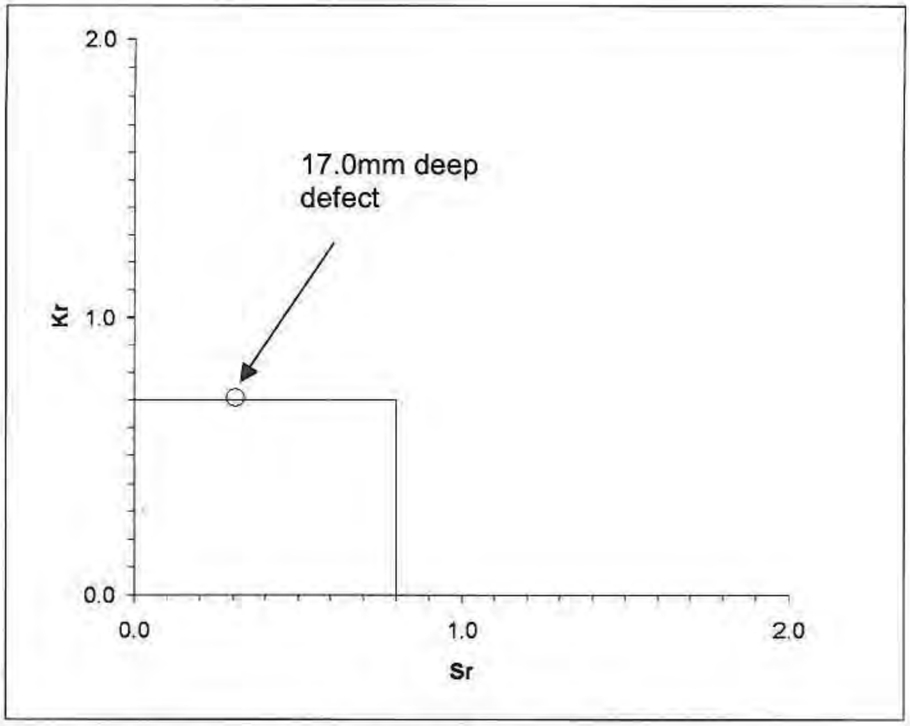


FIGURE A8.1 – FAD FOR SITE L

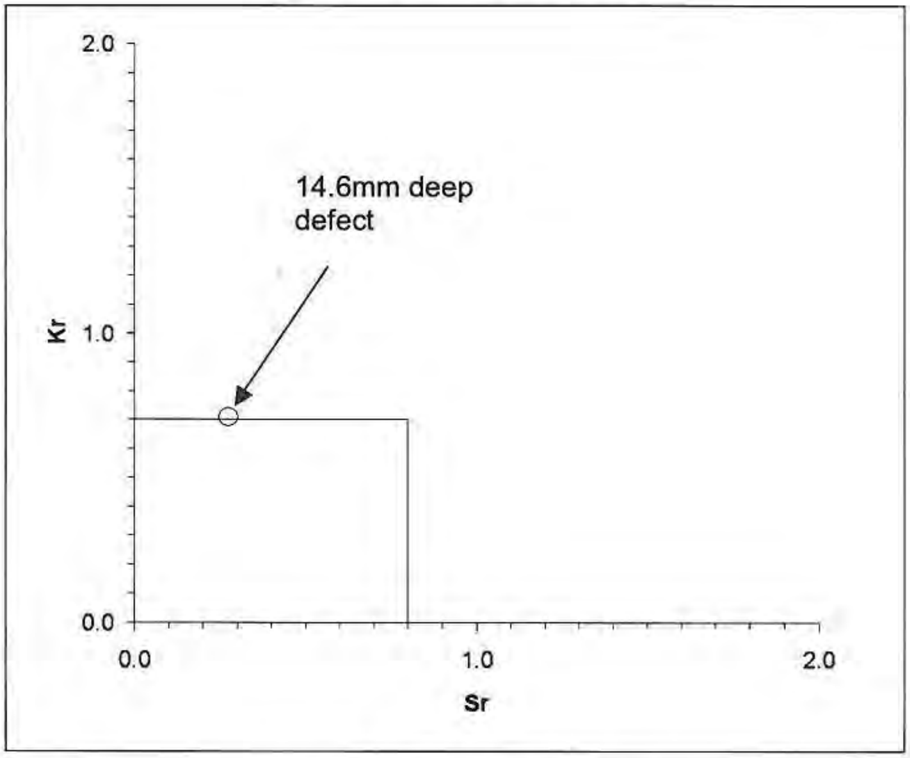


FIGURE A8.2 – FAD FOR SITE 2

# APPENDIX G:

RSG Report (22 pp.)

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**DATE:** 30 September 2009

**CLIENT:** **Battelle**

**CONTRACT NUMBER:** 95786

**JOB TITLE:** EPA Demonstration of Condition Assessment Technologies for Water Mains.

**ADDRESS:**
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# TABLE OF CONTENTS

## 1. EXECUTIVE SUMMARY

Rock Solid Group Pty. Ltd. (RSG) was commissioned by Battelle to participate in a condition assessment program trial on a 24” diameter Cast Iron (CI) water main in Louisville, KY. RSG was also commissioned to undertake post survey processing and analysis of the data collected as well as to provide a written report detailing all findings. The CI water main was scanned externally using the HSK (Hand Scanning Kit) non-destructive testing technique, as well as the CAP (Crown Assessment Probe).

Field testing was conducted from the 24th through to 28th August 2009 by an RSG technician.

Battelle selected a total of nine (9No.) 5-ft long sections to be scanned along the full length of the pipeline. 100% coverage of the full circumference was achieved on all four (4No.) of the HSK scans (excluding adjacent to protrusions such as valves). Another five (5No.) scans were completed using the CAP where only the top portion of the pipe was scanned.

The date of construction of these pipes is unknown. The nominal thickness of the pipe is believed to be approximately 0.650”- 0.700”, however this information should be taken as anecdotal only. Scanning was conducted externally through negligible external coating and soil on the pipes surface, i.e. unprepared surface. The design specifications provided are based on verbal information provided to RSG by Battelle.

From the results obtained it appears that there is some noticeable cylinder thickness loss in most of the pipe sections scanned. There does not appear to be a common wall thinning trend for the entire pipeline length. Most of the wall thinning trends tend to be section specific. Refer to Section 8 – Specific Site Interpretation for description of the condition of the specific scanned sections.

The minimum wall thickness obtained by BEM has been recorded as 0.627” from Site 5 (Pit C).

It must be noted that all plots have the same display parameters and scale to allow for comparisons between scans.

Description of the condition can be found under **section 8 – SPECIFIC SITE INTERPRETATION** and must be read in conjunction with **Appendix A - NDT RESULTS.**

## 2. INTRODUCTION

Rock Solid Group Pty. Ltd. (RSG) was commissioned by Battelle to participate in a condition assessment program trial on a 24” diameter Cast Iron (CI) water main in Louisville, KY. RSG was also commissioned to undertake post survey processing and analysis of the data collected as well as to provide a written report detailing all findings. The CI water main was scanned externally using the HSK (Hand Scanning Kit) non-destructive testing technique, as well as the CAP (Crown Assessment Probe).

Field testing was conducted from the 24th through to 28th August 2009 by an RSG technician.

## 3. TECHNOLOGY DESCRIPTION

The HSK & CAP utilizes Broadband Electro-Magnetic (BEM) technology and can be considered a ‘pulse eddy current’ system. This technology is a derivative of geophysical equipment which has been used in the mineral exploration industry for more than eighty years and is therefore based on well established physics principles.

RSG’s background knowledge of this technology and experience in its use in the exploration industry has allowed for the modification of it for non-destructive testing (NDT) inspections.

Ultrasonic testing, or UT as it is commonly referred to, is probably the most well established material testing technique for assessing ferrous pipe wall conditions. However to call this technique NDT is really a misrepresentation. To not remove coatings or linings or to not ‘polish’ surfaces for good sensor contact means yielding low confidence data.

BEM was developed because existing and available techniques and devices could not give the level of detail and data confidence required for assessments of assets without misrepresentation or unacceptable commercial risk.

External pipe wall condition assessments are typically carried out on all types of ferrous pipelines to explore the integrity of the ferrous pipe wall.

Advantages of the HSK & CAP external inspection system of NDT include:

- Scanning is not limited by the diameter of the pipe.
- Ability to survey through thick coatings (50mm+) of materials such as paint or tar commonly found on many buried and exposed pipelines.
- The line does not have to be taken off-line, as readings are taken from the outside of the pipe. The technique scans through the full wall of pipe registering corrosion or flaws within the full wall thickness.
- Negligible effect of outside stray current fields potentially contaminating resulting data. Where stray fields are identified – these can be clearly seen in captured data – variations in data capture parameters are possible since the device is non-frequency dependent.

## 4. EQUIPMENT

The equipment selected for the NDT scanning of the pipelines was a HSK & CAP system. These ultra-sensitive instruments are capable of generating comprehensive magnetic and electromagnetic images, measuring intensity variation of ferrous material corresponding to the characteristics of pipe wall conditions for identification of degradation due to corrosion or abrasion.

The HSK approach involves an operator to place the antenna on the pipes surface, normally in an excavation pit such as in this project, and ideally with an accurate reference system. Data is acquired and stored on a laptop outside if the pit and the operator moves the antenna around the pipes circumference, and then along the pipes length. Full coverage (100%) is normally obtained in scanning pipes using the HSK method, apart from where obstacles are encountered, such as valves & joints. Refer to Section 5.2 Survey Method for the standard reference system when using the HSK method.

The CAP approach does not require manned entry into the excavation pit. In project work, the pipe would have vacuum excavation applied to the crown region of the pipe and only the area excavated would be available for scanning and assessment. CAP scans do not provide a detailed assessment of the ‘full’ circumference of the pipe but it allows the client to sample many more locations along the pipes length whilst keeping to a limited budget. Refer to Section 5.2 Survey Method for the standard reference system when using the CAP method.

## 5. FIELD TESTING

Field testing was conducted from the 24th through to 28th August 2009 by an RSG technician.

Details of the nine (9No.) locations tested can be found below.

### 5.1 Field Testing Details

**Site 1 – Pit L** *(HSK Method)*
24” ID Grey Cast Iron Pipe; ~ 0.650”- 0.700” nominal wall thickness; negligible coating; cement mortar lined. Up to 5’ in pipe length was available for external scanning. Of this 5ft, 4ft was available for the full circumference. The last foot of pipe was not fully excavated therefore part of the invert could not be scanned. Post-survey processing indicated noise in the BEM data at the crown of the pipe over the first two feet of pipe which is possibly due to nearby underground services.

**Site 2 – Pit F** *(HSK Method)*
24” ID Grey Cast Iron Pipe; ~ 0.650”- 0.700” nominal wall thickness; negligible coating; cement mortar lined. Up to 5’ in pipe length was available for external scanning. 100% coverage was obtained for the whole 5ft pipe section.

**Site 3 – Pit A** *(CAP Method)*
24” ID Grey Cast Iron Pipe; ~ 0.650”- 0.700” nominal wall thickness; negligible coating; cement mortar lined. A pit of approximately 2ft wide was accessible for external scanning with the CAP

tool. Within this 2ft long pit, 1ft length was able to be scanned at 7” wide (around circumference). Scanning was achieved from approximately 11 o’clock to 1 o’clock.

**Site 4 – Pit B** *(CAP Method)*
24” ID Grey Cast Iron Pipe; ~ 0.650”- 0.700” nominal wall thickness; negligible coating; cement mortar lined. A pit of approximately 3ft wide was accessible for external scanning with the CAP tool. Within this 3ft long pit, 2ft length was able to be scanned at 7” wide (around circumference). Scanning was achieved from approximately 11 o’clock to 12 o’clock (not centered on pipes crown).

**Site 5 – Pit C** *(CAP Method)*
24” ID Grey Cast Iron Pipe; ~ 0.650”- 0.700” nominal wall thickness; negligible coating; cement mortar lined. A pit of approximately 3 ½ ft wide was accessible for external scanning with the CAP tool. Within this 3 ½ ft long pit, 2 ½ ft length was able to be scanned at 7” wide (around circumference). Scanning was achieved from approximately 11 o’clock to 1 o’clock.

**Site 6 – Pit D** *(CAP Method)*
24” ID Grey Cast Iron Pipe; ~ 0.650”- 0.700” nominal wall thickness; negligible coating; cement mortar lined. A pit of approximately 1 ½ ft wide was accessible for external scanning with the CAP tool. Within this 1 ½ ft long pit, 1ft length was able to be scanned at 7” wide (around circumference). Scanning was achieved from approximately 10 o’clock to 11 o’clock.

**Site 7 – Pit 2** *(HSK Method)*
24” ID Grey Cast Iron Pipe; ~ 0.650”- 0.700” nominal wall thickness; negligible coating; cement mortar lined. Up to 5’ in pipe length was available for external scanning. 100% coverage was obtained for the whole 5ft pipe section apart from the where the valves protruded the pipe wall.

**Site 8 – Pit F** *(HSK Method)*
24” ID Grey Cast Iron Pipe; ~ 0.650”- 0.700” nominal wall thickness; negligible coating; cement mortar lined. Up to 10’ in pipe length was available for external scanning. 100% coverage was obtained for the whole 10ft pipe section. Site 8 is in the same pit (F) as Site 2 but on a different pipe section separated by a bell & spigot joint.

**Site 9 – Pit E** *(CAP Method)*
24” ID Grey Cast Iron Pipe; ~ 0.650”- 0.700” nominal wall thickness; negligible coating; cement mortar lined. A pit of approximately 1 ½ ft wide was accessible for external scanning with the CAP tool. Within this 1 ½ ft long pit, 1ft length was able to be scanned at 7” wide (around circumference). Scanning was achieved from approximately 9 o’clock to 10 o’clock.

### 5.2 Survey Method

The most preferred procedure is to use pre-plotted grid paper with 2” intervals, taking individual readings around the circumference. The paper would be wrapped around the outside of the pipe allowing for accurate reference points of each individual reading taken.

The NDT grid with survey orientation is schematically illustrated in Figure 1. Scanning would be undertaken from the outside of the pipe along the circumference starting and finishing at the crown of the pipe.

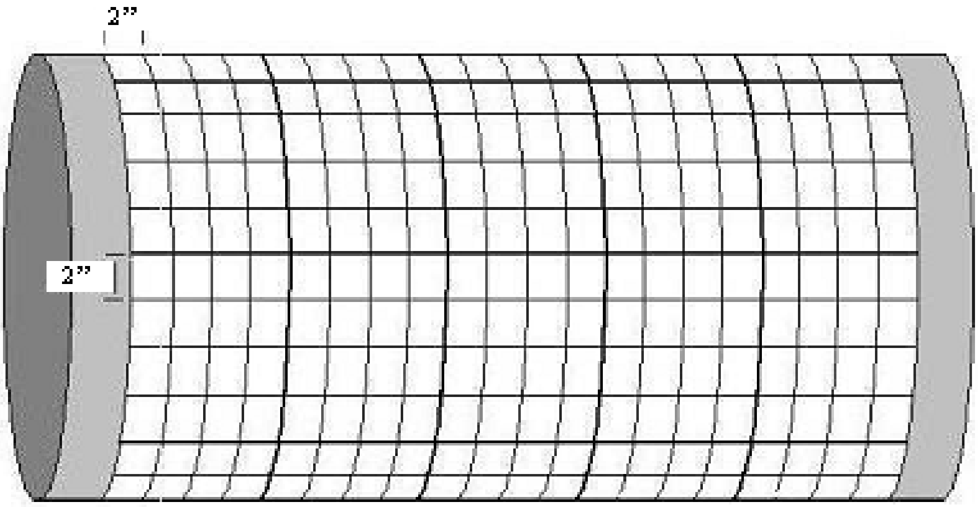


**Figure 1. Typical Survey Grid Along a Pipe Section.**

For this particular project, chalk was used to mark a reference grid on the pipes external surface.

All HSK scans for this project started at the crown of the pipe, moving around the circumference over the invert, and finishing back at the crown of the pipe, see Figure 4 below.

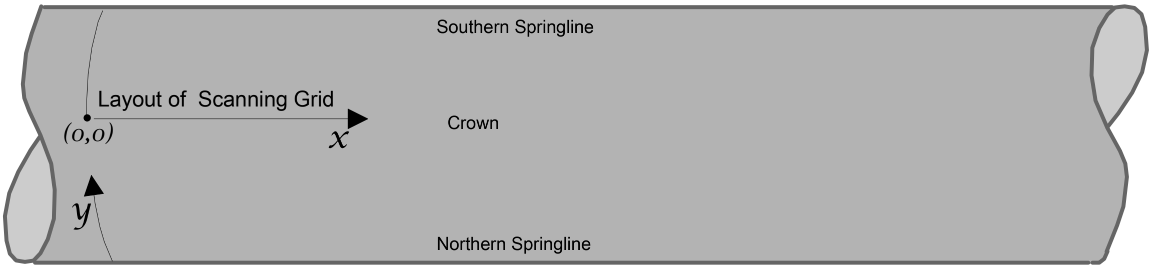
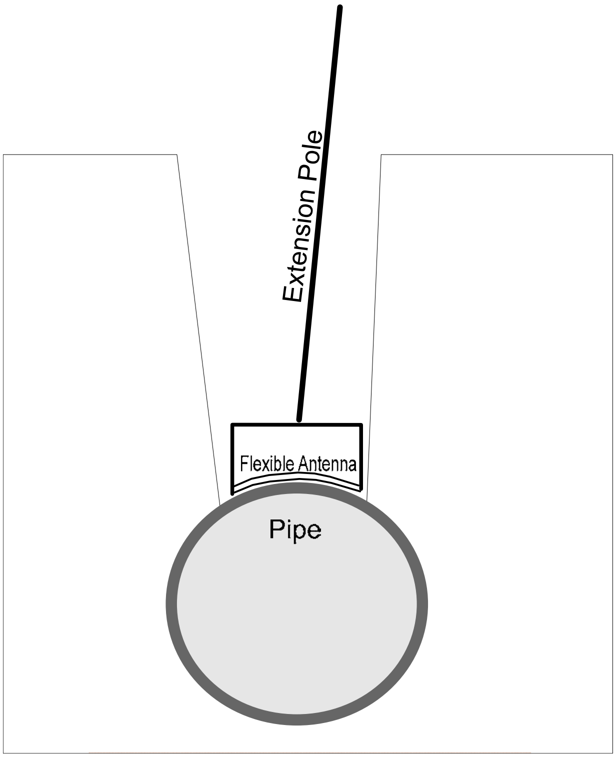


**Figure 2. Plan View of Specific Referencing for Pipe Section Survey.**

Where corrosion occurs or is suspected to occur along the crown of a pipe internally or externally the application of the CAP system is ideally suited. Trends in pipe crown corrosion will only be identified along the length of the pipeline if a suitable number of CAP scans are performed. Antennae are lowered into the vacuum excavated pothole on an extension pole and pressed firmly to the crown of the pipe to allow for good contact between the antenna and pipe. The housing of the antennae is made of flexible material such as cotton to allow for the curvature of the pipe. This allows the antenna to conform with the pipe wall. See figures 1 & 2 below.



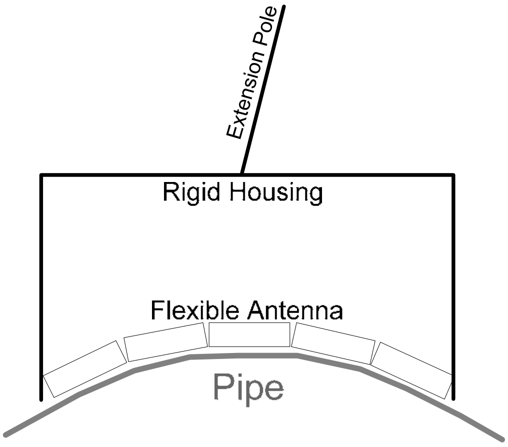


**Figure 3.** **Typical CAP Scan Setup.** **Figure 4.** **Diagram of CAP Design.**

## 6. RESULTS

The collected data was processed using a multi stage screening and processing procedure.

Determination of percentage intensity variation of ferrous material was obtained to facilitate interpretation of pipe characteristics.

The processed data is presented in Appendix A as plots showing the apparent wall thickness of the pipes.

Results have also been provided in excel format with X & Y co-ordinates corresponding to the position of the data readings, and Z Co-ordinate corresponding to apparent wall thickness. All measurements are in inches. Apparent wall thicknesses collected at each reading can be found under the attached file “Battelle01_Data Summary.xls.”

## 7. BEM INTERPRETATION

In a signal to thickness measurement, high amplitude signals represent thicker ferrous material within the sensor’s range of influence while a decrease in signal amplitude corresponds to reduction in ferrous material quality or thickness. With accurate calibration, a thickness conversion against amplitude reduction can be obtained.

Information from our existing database has been combined with specific frequency ranges for conversion to percentage signal variation. These have then been used to predict the ferrous wall condition.

Occurrence of micro structures within the ferrous material makes it impossible to determine an absolute thickness conversion. An added complexity is that the response is averaged over an area and volume scanned by the sensors, in this case approximately 2”² (for HSK scans), or 1”² (for CAP scans).

These limitations render the measurements of an absolute conversion difficult and thus only a relative or apparent thickness correlation is provided in the interpretation.

### a) Averaged Area of Readings

Each sensor averages over an area of approximately 2” square. This means that any anomaly or flaw within or on the pipe wall must be viewed as a percentage of the overall volume of ferrous material scanned. It is therefore important to note that a surface scratch or an isolated pit, unless of significant size with respect to the scanned area, will not be seen as significant and may not have enough impact to affect a particular reading.

It is also not possible to assess whether a noted wall thinning is as a result of ferrous loss on the front or the back of the pipe wall or a combination of both. Similarly a cluster of pits will appear as a general wall thinning rather than a pit cluster.

The BEM plots are a good representation of the area of each flaw and flaw trends. However, a clear understanding of the HSK operation & antenna orientation with respect to the flaw is crucial when determining size of flaws. More often than not a common situation is that a low response from certain number of sensors does not equate to a flaw of that size. i.e. See Figure 3 below, and note that a low response captured from three x 2” sensors would not necessarily be a flaw of 6” in size.

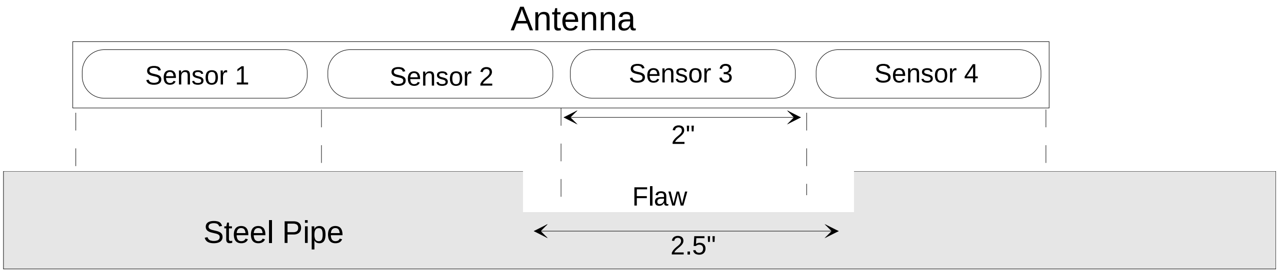


**Figure 5. Representation of Sensors Responding to Flaw.**

Similarly, a flaw small in area ( < 2”x 2”) may be scanned by up to four different sensors, resulting in a thickness contour plot indicating a larger flaw area of lesser wall thinning than the actual situation.

### b) Apparent Wall Thickness

It is not possible to tell whether the pipe wall is thinner or whether the metallurgy of the wall has been altered. Thinning may be the result of original manufacture or abrasion while pipe alteration to rust or graphitisation is a replacement type process rather than a wall thickness reduction based on a physical measurement.

Corroded or altered ferrous material remains conductive and therefore has electromagnetic properties. As a result it has an effect on the overall response recorded by the BEM signal.

It is however important to note that the response from corroded or altered material is significantly weaker and therefore the recorded data is not affected to any great extent. It is also important to understand that corroded or altered material still provides some level of structural support and more importantly, provides an effective barrier for further corrosion since it effectively 'coats' the fresh ferrous material.

### c) Heat Effect

Pipes can be affected by heat processes such at the welding of steel pipes. This heating of the pipe can potentially alter the metallurgy of the steel. The altered metallurgy of the steel can create an area on the pipe that is more susceptible to corrosion. These processes can alter the way the HSK responds to ferrous material. This is can be evident in the scan plot and is exhibited as an apparent drop or rise in pipe wall thickness in close proximity of welds.

### d) Manufacture Processes

Pipes can also be affected by manufacturing processes such as rolling. These processes can alter the way the BEM responds due the affected area. This will be evident in the scan plot and is exhibited as an apparent drop or rise in pipe wall thickness that is normally evident in a consistent trend.

## 8. SPECIFIC SITE INTERPRETATION

### Site 1 – Pit L

The scan shows areas of reduced thickness to a minimum of 0.654” with the average thickness around 0.735”. Relative high degree of wall thinning on this scanned section appears to be near the crown of the pipe, and relatively moderate wall thinning at the pipes haunches. There was a section at the pipes invert that could not be scanned due to the pipe not being fully excavated at this location. There are also two sections where the BEM data could not be processed as there was noise interference in close proximity to this region. It is believed that as the noisy interference was only observed in this single area that it is due to a nearby underground source such as electricity cables.

### Site 2 – Pit F

The scan shows areas of reduced thickness to a minimum of 0.678” with the average thickness around 0.745”. There are isolated areas of relative high degree of wall thinning on this scanned section appears to be near the crown of the pipe, and relatively moderate wall thinning at the pipes haunches. Due to the thinning appearing in isolated areas and not that of a particular trend, it is probable that this type of wall loss is due to pit clusters or graphitisation.

**Site 3 – Pit A**
The scan shows areas of reduced thickness to a minimum of 0.662” with the average thickness around 0.737”. This CAP scan only covers a small area limited to the excavation, however relatively moderate corrosion still appears to have been recorded near the crown of this pipe section.

**Site 4 – Pit B**
The scan shows areas of reduced thickness to a minimum of 0.680” with the average thickness around 0.719”. This CAP scan only covers a small area that is limited to the excavation, however relatively moderate corrosion still appears to have been recorded near the crown of this pipe section.

**Site 5 – Pit C**
The scan shows areas of reduced thickness to a minimum of 0.627” with the average thickness around 0.703”. This CAP scan only covers a small area that is limited to the excavation, however relatively severe corrosion appears to have been recorded across the majority of this scan near the crown of this pipe section.

**Site 6 – Pit D**
The scan shows areas of reduced thickness to a minimum of 0.666” with the average thickness around 0.689”. This CAP scan only covers a small area that is limited to the excavation, however relatively moderate corrosion still appears to have been recorded near the crown of this pipe section.

**Site 7 – Pit 2**
The scan shows areas of reduced thickness to a minimum of 0.688” with the average thickness around 0.735”. There appears to be relatively moderate-to-severe corrosion on the southern haunch of the pipe, as well as a fairly convincing trend of moderate corrosion at the invert of the pipe.

**Site 8 – Pit F**
The scan shows areas of reduced thickness to a minimum of 0.711” with the average thickness around 0.748”. There appears to be relatively moderate corrosion on both the southern and northern haunches of the pipe, but more-so on the northern side.

**Site 9 – Pit E**
The scan shows areas of reduced thickness to a minimum of 0.704” with the average thickness around 0.709”. This CAP scan only covers a small area that is limited to the excavation, and negligible wall thickness variation was recorded at this location. After confirmation of original wall thickness, an assumption could be made if general wall thinning has occurred over this entire scanned section.

## 9. NDT CONCLUSIONS & RECOMMENDATIONS

Rock Solid Group Pty. Ltd. (RSG) was commissioned by Battelle to participate in a condition assessment program trial on a 24” diameter Cast Iron (CI) water main in Louisville, KY. RSG was also commissioned to undertake post survey processing and analysis of the data collected as well as to provide a written report detailing all findings. The CI water main was scanned externally using the HSK (Hand Scanning Kit) non-destructive testing technique, as well as the CAP (Crown Assessment Probe).

Field testing was conducted from the 24th through to 28th August 2009 by an RSG technician.

The date of construction of these pipes is unknown. The nominal thickness of the pipe is believed to be approximately 0.650”- 0.700”, however this information should be taken as anecdotal only. Scanning was conducted externally through negligible external coating and soil on the pipes surface, i.e. unprepared surface. The design specifications provided are based on verbal information provided to RSG by Battelle.

From the results obtained it appears that there is some noticeable cylinder thickness loss in most of the pipe sections scanned. There does not appear to be a common wall thinning trend for the entire pipeline length. Most of the wall thinning trends tend to be section specific. Refer to Section 8 – Specific Site Interpretation for description of the condition of the specific scanned sections.

The minimum wall thickness obtained by BEM has been recorded as 0.627” from Site 5 (Pit C).

As it is known that this pipe has been taken offline and no longer in use, RSG have no further recommendations for BEM assessment of this pipeline.

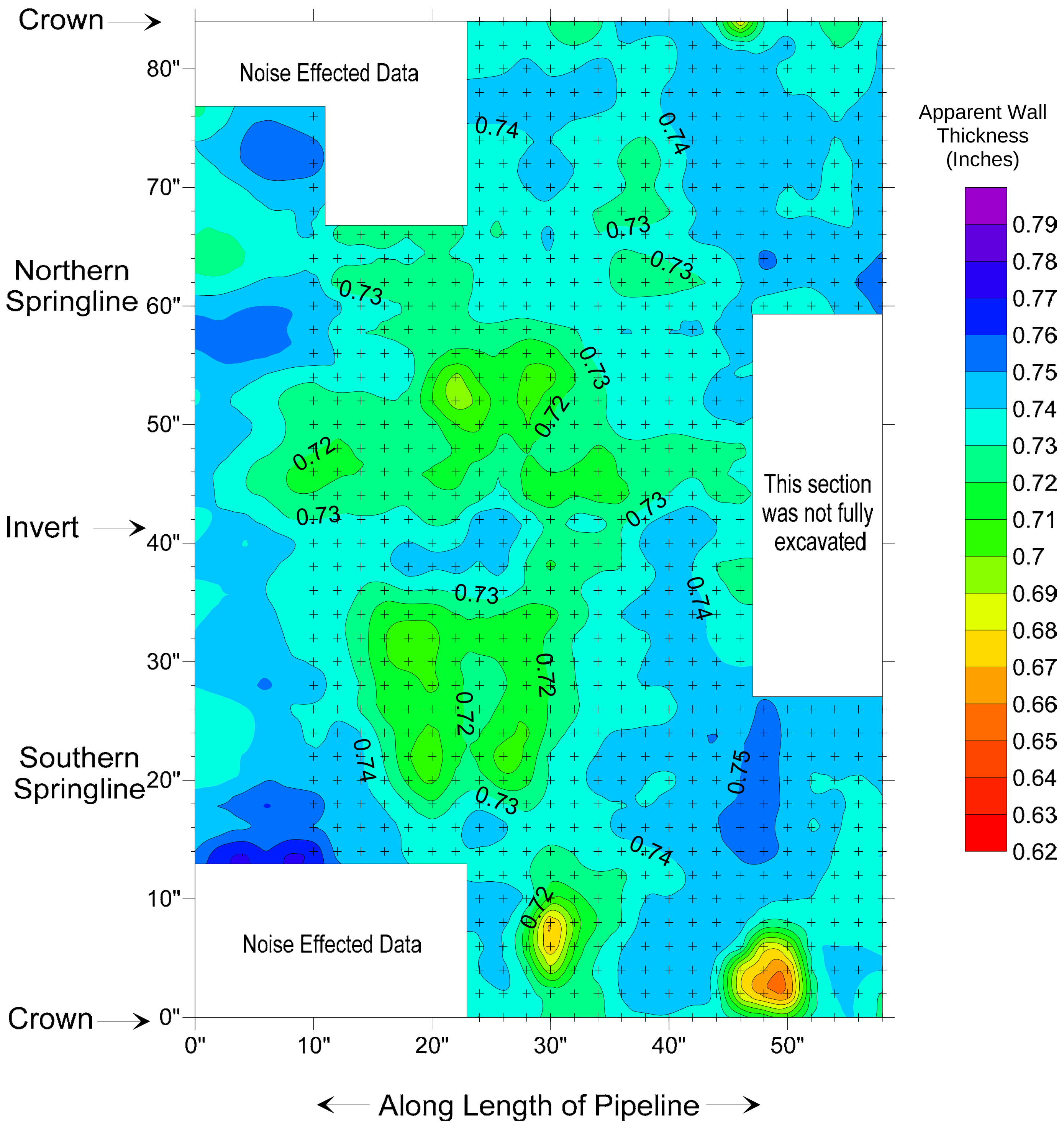
Description of the condition can be found under **section 8 – SPECIFIC SITE INTERPRETATION** and must be read in conjunction with **Appendix A - NDT RESULTS.**

# APPENDIX A NDT RESULT

# Battelle - Site 1 – Pit L

## EPA Demonstration of Condition Assessment Technologies

### 24” Diameter Cast Iron Pipe



**ROCK SOLID GROUP**

ABN: 86 760 170 879

**LEGEND:**

\+ Scan Location

0.8 Thickness Contour

TITLE: EPA DEMONSTRATION OF CONDITION ASSESSMENT TECHNOLOGIES FOR WATER MAINS, LOUISVILLE, KY
OCT 2009

ID: Site 1
Pit L

CLIENT: **Battelle**

PROJECT NO.: 95786

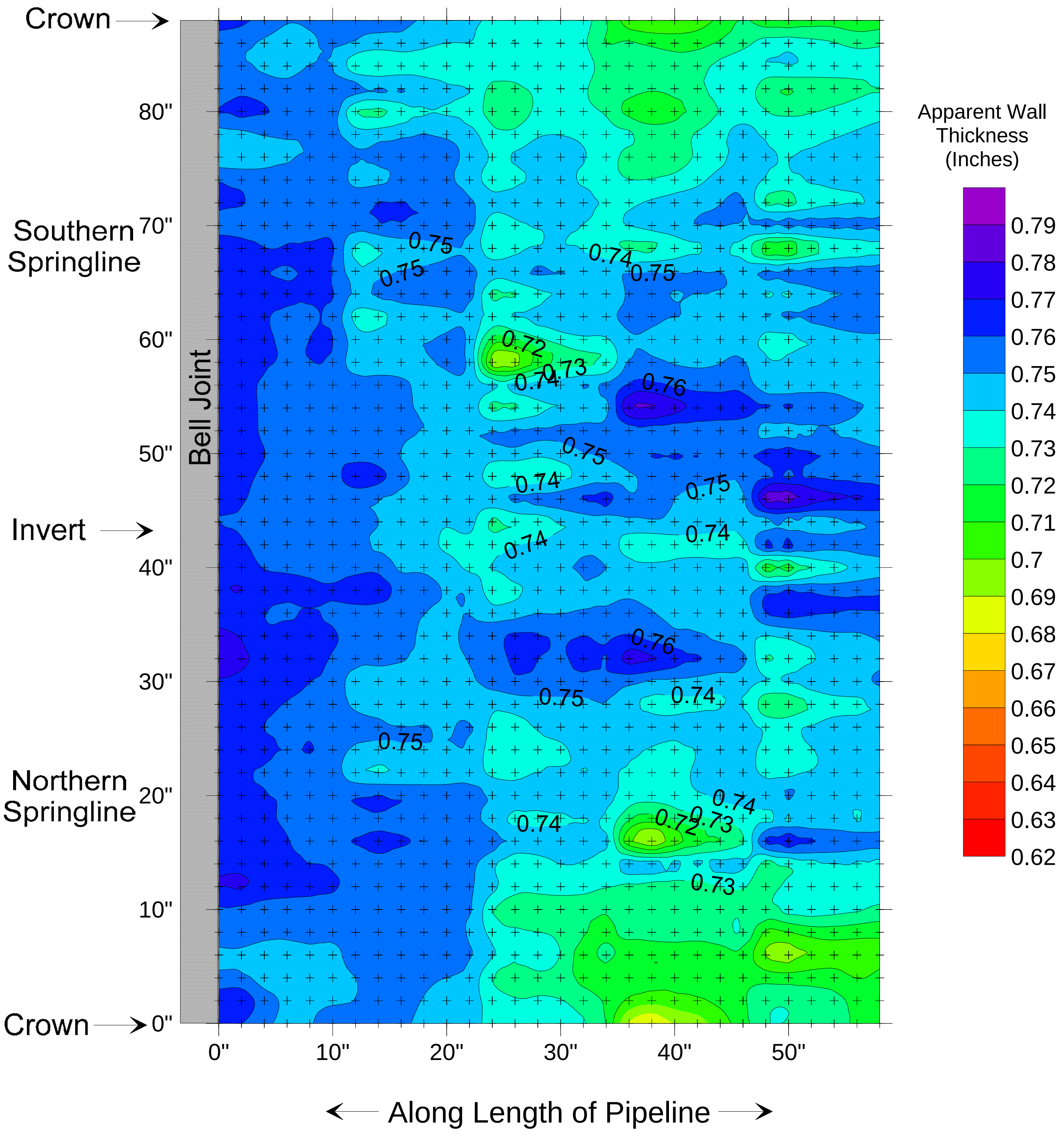
PREPARED BY: MARK DISHON

DATE: SEPT 2009

# Battelle - Site 2 – Pit F

## EPA Demonstration of Condition Assessment Technologies

24” Diameter Cast Iron Pipe



**ROCK SOLID GROUP**

ABN: 86 760 170 879

**LEGEND:**

\+ Scan Location

0.8 Thickness Contour

TITLE: EPA DEMONSTRATION OF CONDITION ASSESSMENT TECHNOLOGIES FOR WATER MAINS, LOUISVILLE, KY
OCT 2009

ID: Site 2
Pit F

CLIENT: **Battelle**

PROJECT NO.: 95786

PREPARED BY: MARK DISHON

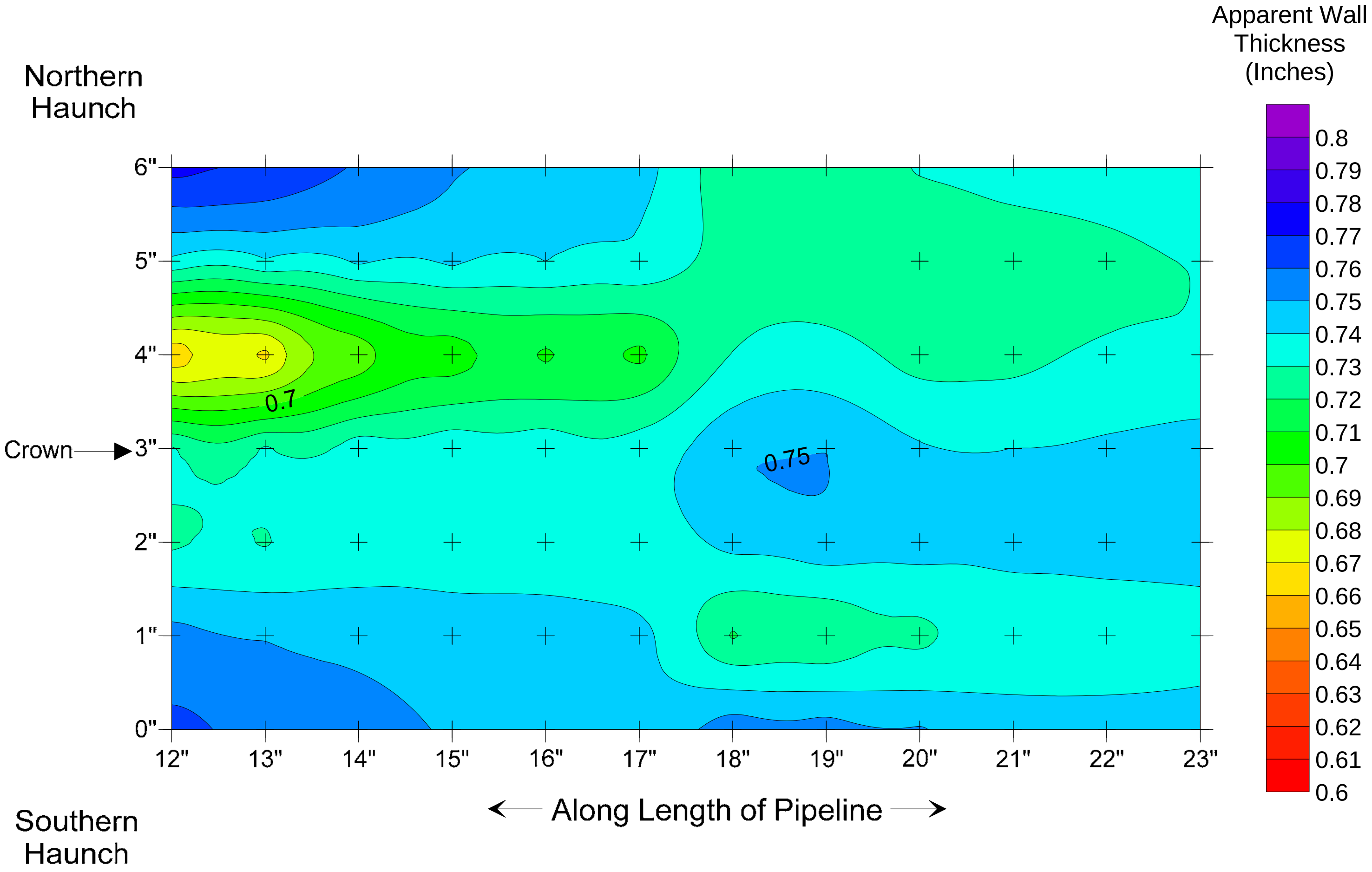
DATE: SEPT 2009

# Battelle - Site 3 – Pit A

EPA Demonstration of Condition Assessment Technologies

24" Diameter Cast Iron Pipe

*(CAP Scan Only)*



ROCK SOLID GROUP

ABN: 86 760 170 879

**LEGEND:**

+ Scan Location

0.8 Thickness Contour

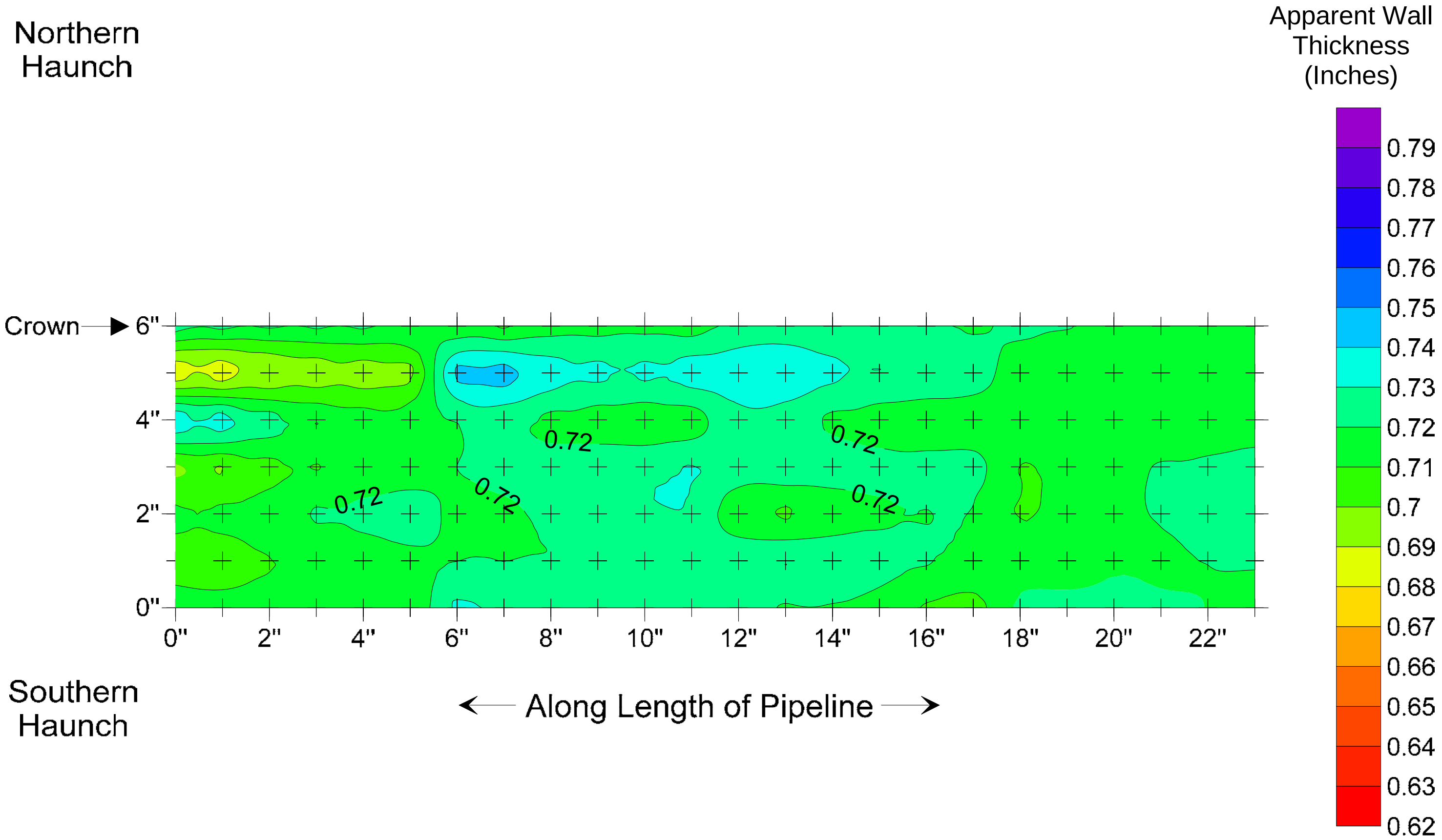
| | | | |
|---|---|---|---|
| TITLE: | EPA DEMONSTRATION OF CONDITION<br>ASSESSMENT TECHNOLOGIES FOR<br>WATER MAINS, LOUISVILLE, KY<br>OCT 2009 | ID: | Site 3<br>Pit A |
| CLIENT: | **Battelle** | | |
| PROJECT NO.: 95786 | PREPARED BY: MARK DISHON | DATE: SEPT 2009 | |

# Battelle - Site 4 – Pit B

## EPA Demonstration of Condition Assessment Technologies

24” Diameter Cast Iron Pipe

*(CAP Scan Only)*



ROCK SOLID GROUP

ABN: 86 760 170 879

**LEGEND:**

+ Scan Location

0.8 Thickness Contour

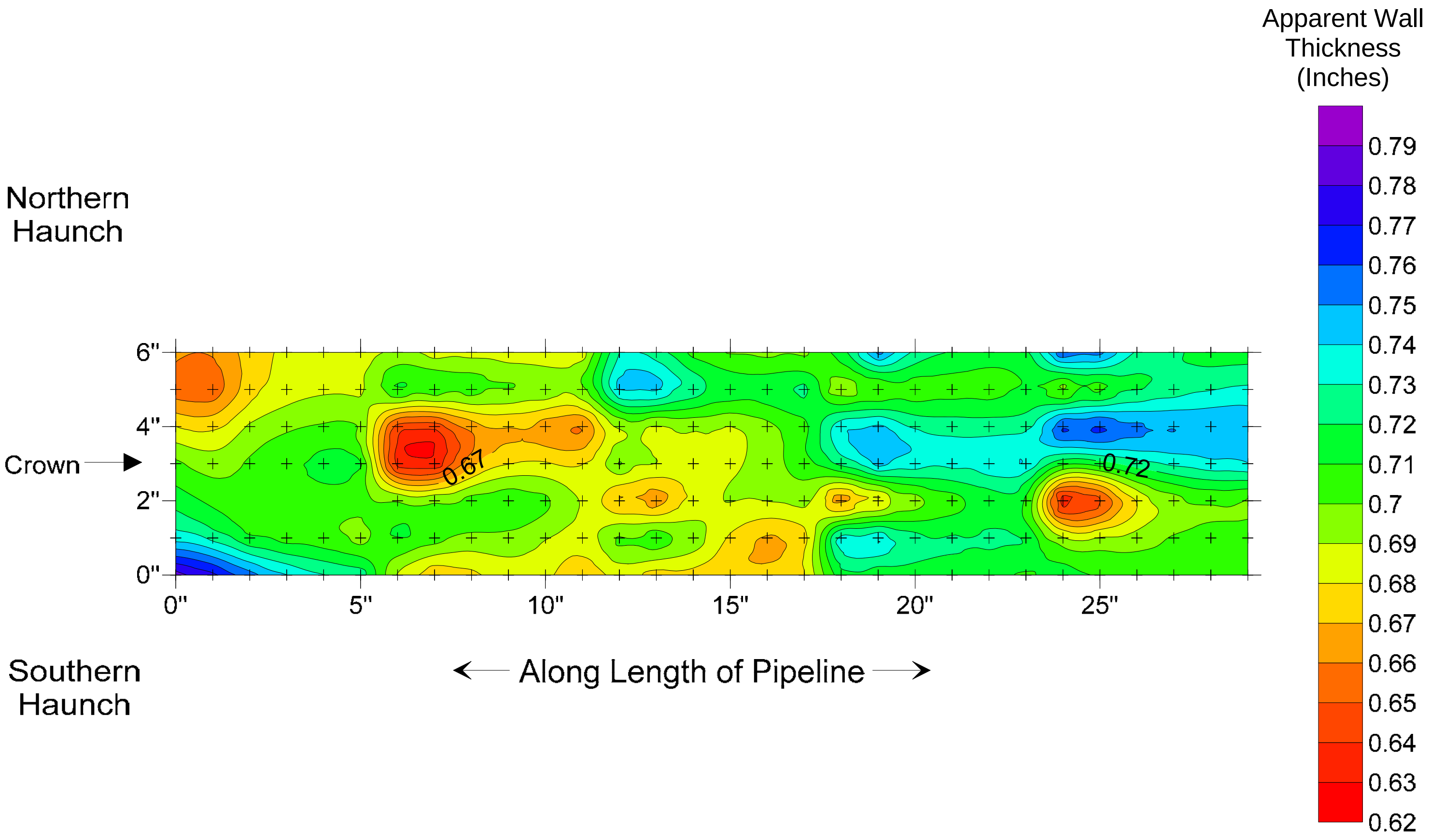
| | | | |
|---|---|---|---|
| TITLE: | EPA DEMONSTRATION OF CONDITION ASSESSMENT TECHNOLOGIES FOR WATER MAINS, LOUISVILLE, KY<br>OCT 2009 | ID: | Site 4<br>Pit B |
| CLIENT: | **Battelle** | | |
| PROJECT NO.: 95786 | PREPARED BY: MARK DISHON | DATE: | SEPT 2009 |

# Battelle - Site 5 – Pit C

## EPA Demonstration of Condition Assessment Technologies

24” Diameter Cast Iron Pipe

*(CAP Scan Only)*



**ROCK SOLID GROUP**

ABN: 86 760 170 879

**LEGEND:**

\+ Scan Location

0.8 Thickness Contour

| | | | |
|---|---|---|---|
| TITLE: | EPA DEMONSTRATION OF CONDITION ASSESSMENT TECHNOLOGIES FOR WATER MAINS, LOUISVILLE, KY<br>OCT 2009 | ID: | Site 5<br>Pit C |
| CLIENT: | **Battelle** | | |

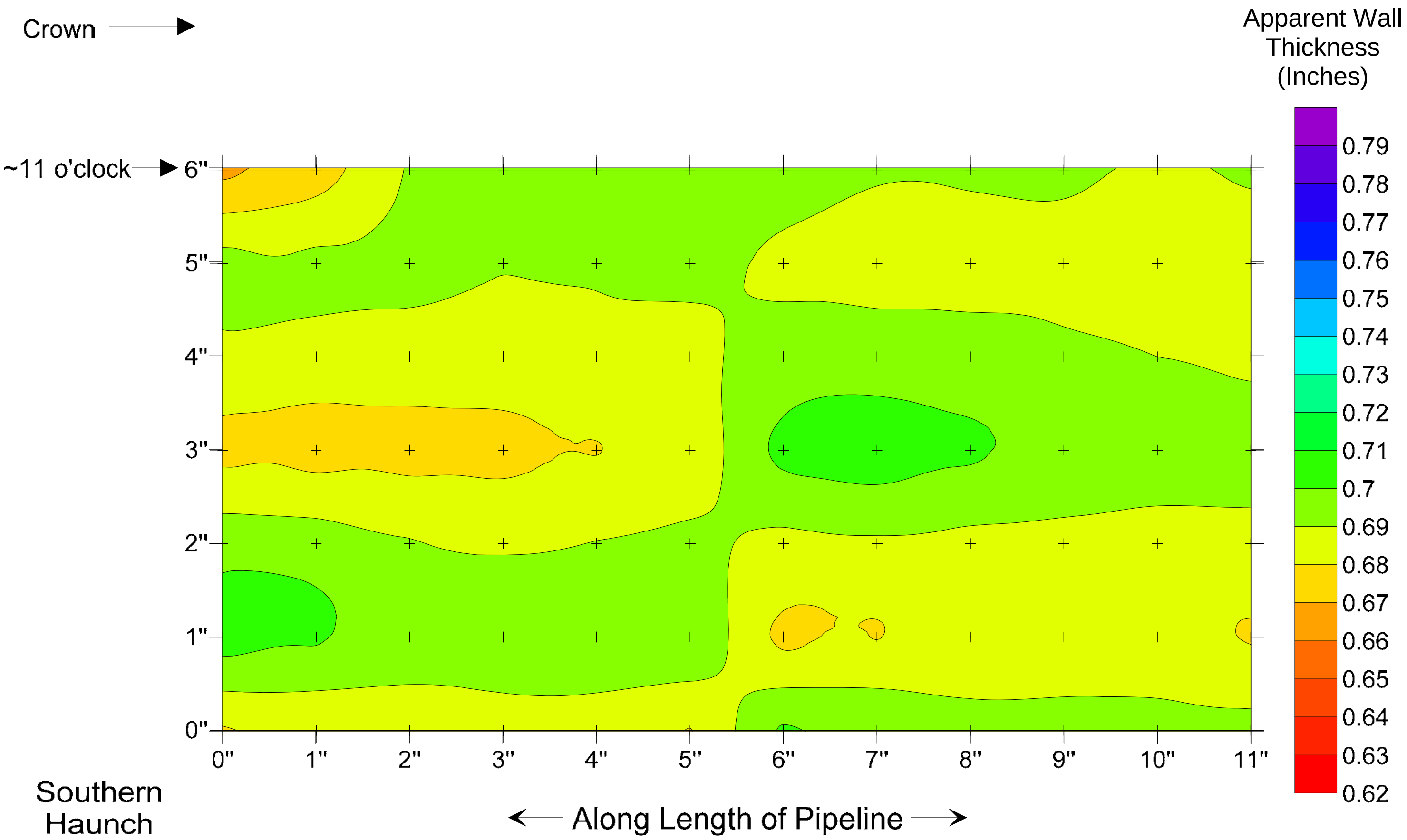
| PROJECT NO.: | PREPARED BY: | DATE: |
|---|---|---|
| 95786 | MARK DISHON | SEPT 2009 |

# Battelle - Site 6 – Pit D

## EPA Demonstration of Condition Assessment Technologies

24” Diameter Cast Iron Pipe

*(CAP Scan Only)*



**ROCK SOLID GROUP**

ABN: 86 760 170 879

**LEGEND:**

\+ Scan Location

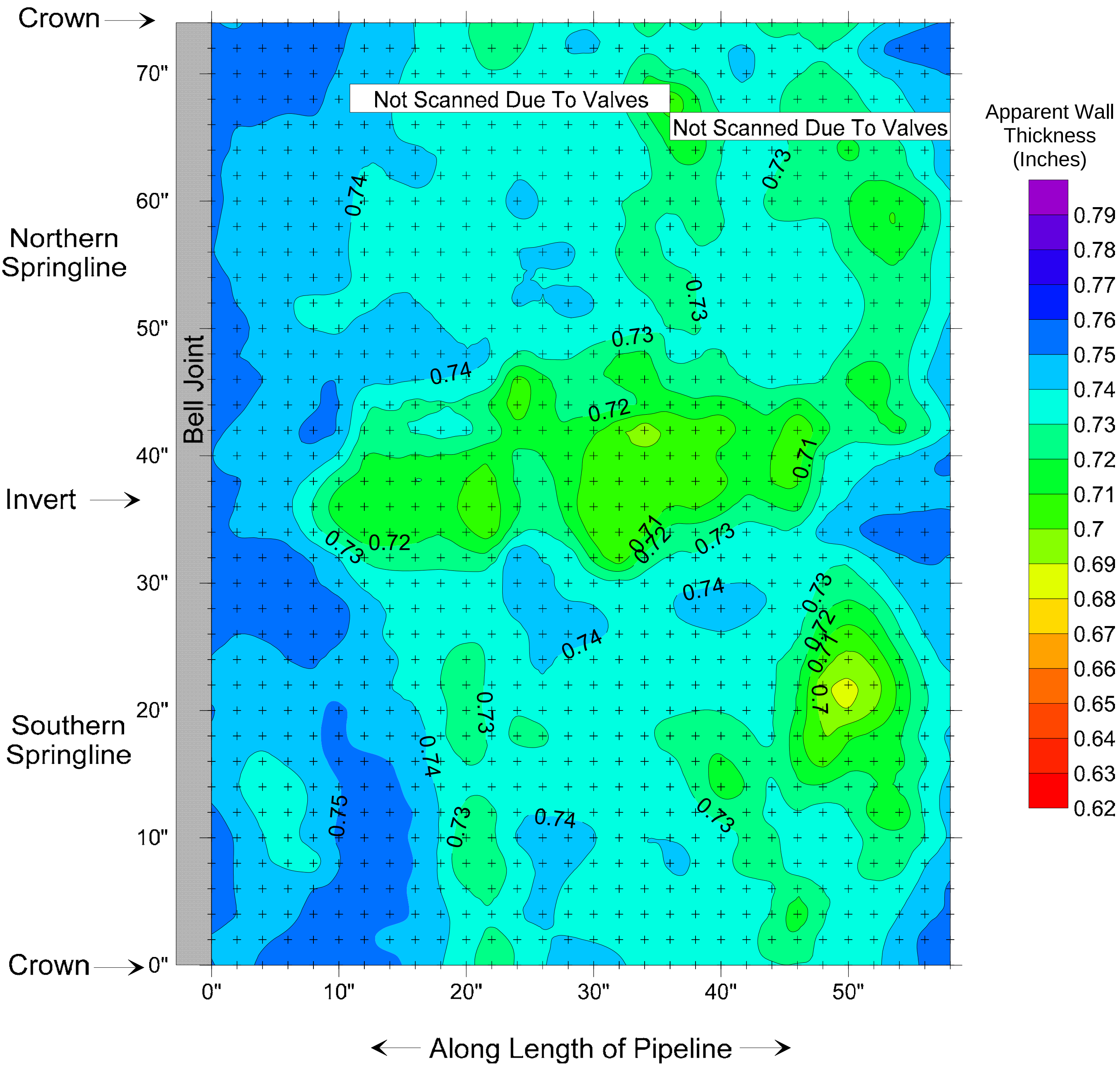
0.8 Thickness Contour

| | | | |
|---|---|---|---|
| TITLE: | EPA DEMONSTRATION OF CONDITION ASSESSMENT TECHNOLOGIES FOR WATER MAINS, LOUISVILLE, KY<br>OCT 2009 | ID: | Site 6<br>Pit D |
| CLIENT: | **Battelle** | | |
| PROJECT NO.: 95786 | PREPARED BY: MARK DISHON | DATE: SEPT 2009 | |

# Battelle - Site 7 – Pit 2

## EPA Demonstration of Condition Assessment Technologies

24” Diameter Cast Iron Pipe



ROCK SOLID GROUP

ABN: 86 760 170 879

**LEGEND:**

\+ Scan Location

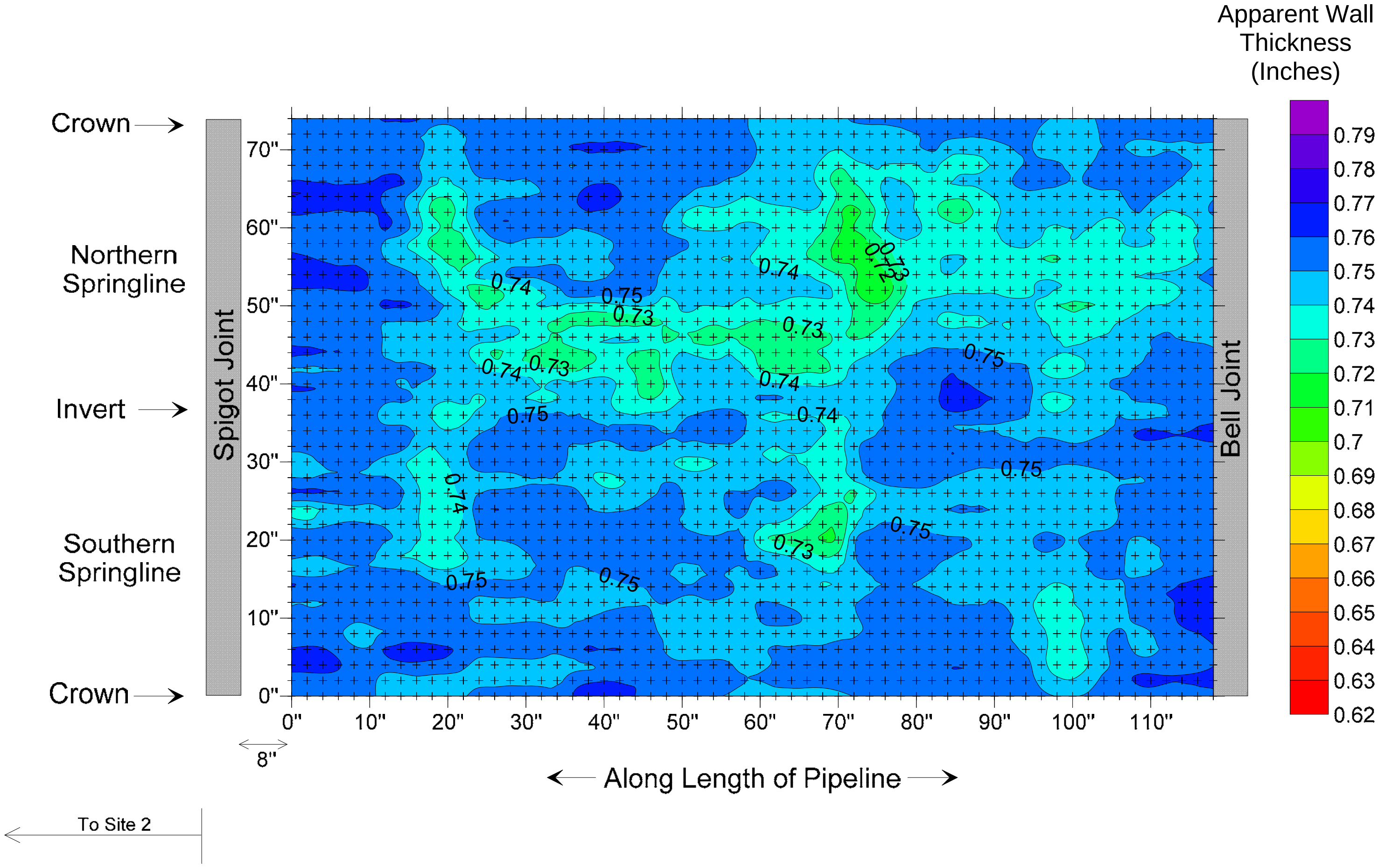
0.8 Thickness Contour

| | | | |
|---|---|---|---|
| TITLE: | EPA DEMONSTRATION OF CONDITION ASSESSMENT TECHNOLOGIES FOR WATER MAINS, LOUISVILLE, KY<br>OCT 2009 | ID: | Site 7<br>Pit 2 |
| CLIENT: | **Battelle** | | |
| PROJECT NO.: 95786 | PREPARED BY: MARK DISHON | DATE: SEPT 2009 | |

# Battelle - Site 8 – Pit F

## EPA Demonstration of Condition Assessment Technologies

### 24” Diameter Cast Iron Pipe



ROCK SOLID GROUP

ABN: 86 760 170 879

**LEGEND:**

+ Scan Location

0.8 Thickness Contour

TITLE: EPA DEMONSTRATION OF CONDITION
ASSESSMENT TECHNOLOGIES FOR
WATER MAINS, LOUISVILLE, KY
OCT 2009

ID: Site 8
Pit F

CLIENT: **Battelle**

PROJECT NO.: 95786

PREPARED BY: MARK DISHON

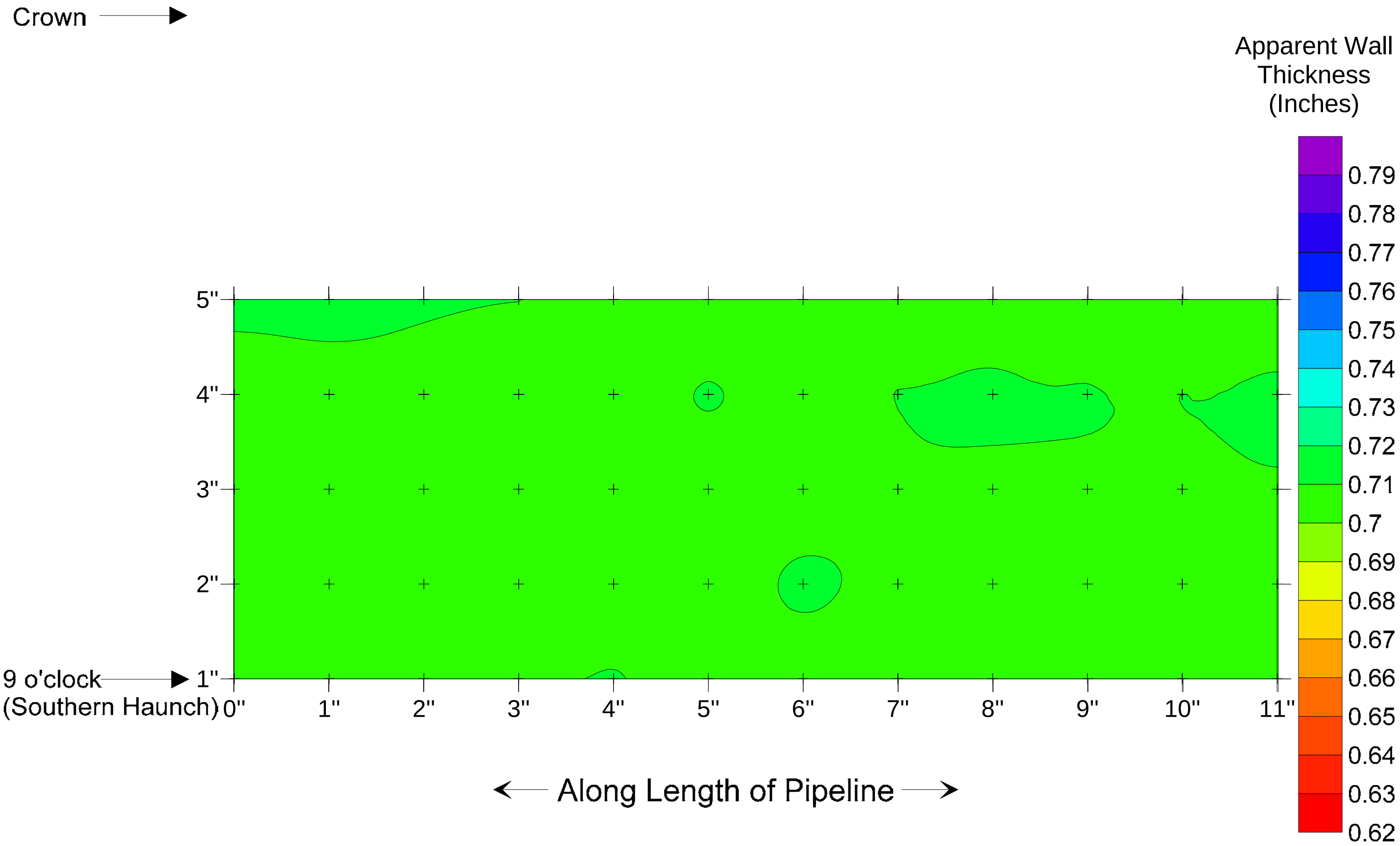
DATE: SEPT 2009

# Battelle - Site 9 – Pit E

## EPA Demonstration of Condition Assessment Technologies

24” Diameter Cast Iron Pipe

*(CAP Scan Only)*



**ROCK SOLID GROUP**

ABN: 86 760 170 879

**LEGEND:**

+ Scan Location

0.8 Thickness Contour

|  |  |  |  |
|---|---|---|---|
| TITLE: | EPA DEMONSTRATION OF CONDITION<br>ASSESSMENT TECHNOLOGIES FOR<br>WATER MAINS, LOUISVILLE, KY<br>OCT 2009 | ID: | Site 9<br>Pit E |
| CLIENT: | **Battelle** |  |  |
| PROJECT NO.: 95786 | PREPARED BY: MARK DISHON | DATE: SEPT 2009 |  |

# APPENDIX H:

## Technology Vendor Letters (8 pp.)

# APPENDIX H

## Technology Vendor Letters

# Response to Final Report

Pure Technologies Ltd.

The following comments are in response to the draft copy of Battelle's report entitled, "Field Demonstration of Innovative Condition Assessment Technologies for Water Mains at Louisville, Kentucky, Part 2: ACOUSTIC PIPE WALL ASSESSMENT, INTERNAL INSPECTION, AND EXTERNAL INSPECTION".

In July, 2010 Pure Technologies (Pure) announced the acquisition of the Pressure Pipe Inspection Company (PPIC) and now represents all of the technologies demonstrated by both parties during the 2009 demonstrations.

## Technology Advancements

The following is a summary of all technology advancements related to the 2009 demonstrations in Louisville, KY.

### Acoustic Pipe Wall Assessment

- **PWA:** During the 2009 field trials, Pure demonstrated SmartBall® Pipe Wall Assessment (PWA) and PPIC (now part of Pure) demonstrated Sahara® Wall Thickness Assessment (WTA). Since PWA's method of capturing data provides higher resolution than WTA, PWA has since been applied to the Sahara platform. A new dual-hydrophone system has been developed for Sahara and as such, Sahara PWA has replaced Sahara WTA.

### Internal Inspections

- **Sahara:** During the 2009 field trials, the Sahara leak detection and video inspections were performed during separate runs and required a sensor head change. Since then, a combined audio/video sensor head has been developed, which allows leak detection and video inspections to be performed simultaneously in the same run.

- **PipeDiver™:** The PipeDiver RFEC tool was equipped with a center detector and six petal detectors during the field trials; however the results from the center detector were only reported due to the lack of calibration data at that time. Since 2009, Pure has performed several pilots with the 6 detector system.

- **Magnetic Flux Leakage:** Realizing the need for high-resolution inline inspections of ferrous water mains, Pure acquired Electromechanical Technologies (EMTEK) and their suite of inline MFL tools in 2011. EMTEK has advanced the MFL technology to incorporate extra high-resolution (XHR) technology, which is able to scan through inner pipe linings up to 1 inch thick and is proven to detect pitting as small as ¼ inches in steel pipe. XHR-MFL is a premium technology complementing Pure's PWA and RFEC technologies.

**Nestleroth, J Bruce**

---

**Subject:** FW: New files waiting for you at Battelle's File Exchange

**From:** Dave Johnston [mailto:DJohnston@echologics.com]
**Sent:** Friday, September 09, 2011 8:35 AM
**To:** Nestleroth, J Bruce
**Cc:** Marc Bracken
**Subject:** RE: New files waiting for you at Battelle's File Exchange

After careful review of the report I am happy to say that we do not have any comments or concerns about the report itself. It was very well written and we feel that the conclusions were fair.

In hindsight, we learned, and are continuing to learn from the results of the report. Currently we are reviewing the results in detail to try and establish a more accurate model of the sensitivity of the method i.e. the ability to find smaller, more isolated pockets of corrosion. This will allow us to make more educated conclusions from a set of results.

In addition to this, we have been continually improving the accuracy and the precision of the method. The most recent development involves a calibration device to account for local water conditions.

One of the most interesting things that was discovered during the field testing in Louisville was the discovery that we could identify the existence of air pockets. As you will recall it actually impeded our ability to perform the tests during our first mobilization. Using what we learned on-site we have developed a procedure to identify large air/gas pockets in water and sewer mains.

Again, we would like to thank you for the opportunity to participate in this study and we would be happy to participate in another, not only to promote Echologics, but to learn from the experience and continue to improve the technology.

Kind Regards

Dave Johnston

RUSSELL
NDT SYSTEMS INC

## Russell (PICA) Comments

### Comments on the report results

1) We are not surprised by the fact that PICA's 24" Tool provided the most accurate and informative information. Russell (PICA) has had over 20 years of developing this technology for a range of pipeline and other applications and, while this particular Tool size was brand new at the time, the fundamental technique has plenty of experience in similar materials and applications (just different pipe sizes). The colour map below shows an example of See Snake data. The image is the RFT wall thickness representation for the pipe length between joints 24 and 25. The reported 70% and 87% deep defect are clearly visible, as are a number of smaller less severe indications.

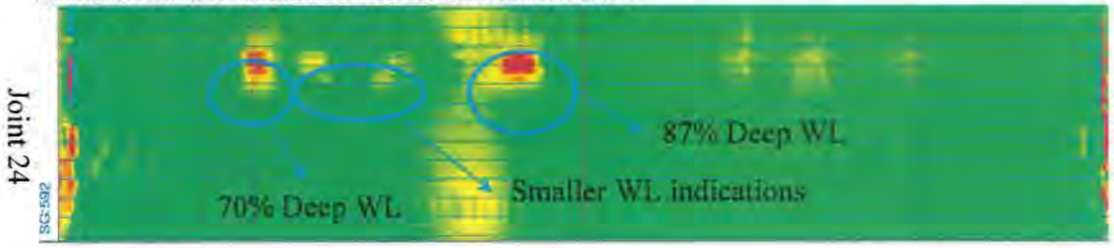


**Figure 1. Colour map of See Snake RFT data for pipelength between joints 24 and 25. Red localized indications depict areas of substantial wall loss (WL).**

2) We were pleased to see that the excavation and confirmation of defects was done in a very careful, professional and accurate manner. During retrieval of pipes it is very easy to mis-number the pipe, but in this case there was a great deal of care and attention given to this important aspect of the project.

3) Russell (PICA) had manufactured the 24" Tool especially in order to be able to participate in this technology evaluation. The report correctly states that the Tool used was not suitable for live launch (free swimming). This is mainly because we did not have time to add an odometer section before the time window for the evaluation expired. Normally, this inspection would have been performed in free-swimming mode, and the problems that we had in coordinating the winches that were attached to both ends of the Tool would not have been an issue. The speed of the Tool in a pipeline that is in service is controlled by the water flow, and surging is not usually an issue.

4) Since the technology demo, Russell has transferred its water and waste water inspection business to PICA: Pipeline Inspection and Condition Analysis Corp., which now has offices in Edmonton, Toronto, Vancouver and Montreal (all Canada) and Charlotte, NC. www.picacorp.com. Tools are available in sizes from 3" to 28".

**Lessons learned from the inspection**

1) We had not used a two-winch set-up before. The first run resulted in surging because we could not keep the two winches synchronized. After the first run, we realized that the trailing winch only needed to be operated in low speed (i.e. rather than trying to rely on a mechanical brake to hold back the winch drum). This improvement allowed the winch that was pulling to have a steady load, and reduced surging to almost zero.
2) The assembly of the Tool took too long. This was because the Tool was new, and was shipped in three sections. In future, we plan to pre-assemble the three parts of the Tool above ground and launch the Tool into an in-service pipeline through launch piping.
3) For similar technology demos we recommend performing low-field electromagnetic type inspections prior to inspection technologies subjecting the pipe to strong magnetic fields (if tool and personnel scheduling and availability allow).

**Improvements made since the demo**

1) The Tool is now configured for free-swimming, pressurized pipeline service.
2) The Tool now has on-board redundant odometers
3) If the application calls for a tethered operation, we have a Standard Operating Procedure to prevent surging
4) Improved resolution and pressure proofing of the detectors
5) PICA-USA Office opened in Charlotte.

# BEM TECHNOLOGY UPDATE
## Rock Solid Group Pty. Ltd.

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- AUSTRALIA
- CANADA
- CZECH REPUBLIC
- HONG KONG
- HUNGARY
- UNITED KINGDOM
- USA

The following is a summary of major advancements which have occurred in BEM technology since the scanning conducted in the EPA Louisville, Kentucky trials by Rock Solid Group in August 2009.

### Technology Advancements

### Software

In 2011 RSG launched its new acquisition software MetCon©. This software greatly increases the ability for the operator to report the wall condition on site in real-time as well as many other benefits such as the ability to make a judgement about the ferrous material being scanned.

### EXTERNAL INSPECTIONS

**Hand Scanning Kit (HSK)** – 2010 saw the launch of the HSK 300 system which is now equipped standard with a full range of 1" & 2" sensor antennae allowing for a selection of desired sensitivity. Besides the battery pack, the HSK 300 can now also be to be powered from a car cigarette lighter or mains power allowing for unrestricted time use. Furthermore, the HSK 300 can now be integrated with Master or Slave Switchers allowing the HSK 300 to power many tens of antennae at the same time. Previously non-scannable pipe components such as elbows can now be tackled easily.

**Crown Assessment Probe (CAP)** – 2011 saw the launch of a commercially available 1" & 2" sensor pipe crown scanning tool. Operating on the back of the HSK 300 the CAP is now being used commercially in scanning of pipe segments through keyholes or potholes, greatly enhancing site safety.

**Full Assessment Probe (FAP)** – On the back of the success of the CAP the development of the FAP has been completed. The FAP allows for the full encirclement of the pipe with BEM antennae in a keyhole or pothole achieving a 100% pipe wall coverage about the exposed section of pipe with no need for manned entry, greatly enhancing site safety.

**Wall Assessment Probe (WAP)** – 2011 saw the launch of a commercially available 1" & 2" sensor wall scanning tool. It is ideal for and has been applied to the scanning of water storage tanks and the like. Operating on the back of the HSK 300 the WAP is now being used commercially to scan large patches of tank walls simultaneously.

### INTERNAL INSPECTIONS

**Hand Scanning kit (HSK)** – The HSK has been applied to the internal scanning of pipe wall and elbows where manned entry is available. Specifically pipe components such as elbows, which do not lend themselves to PIG scanning can now be assessed with both 1" & 2" sensor antennae.

**Pipe Inspection Gauge (PIG)** – Although minor pipe lengths were scanned using remotely operated PIG units equipped with BEM technology the launch of significant in-line scanning occurred in early 2010. The ability to now control numerous BEM consoles with the aid of enhanced software, switching devices which allow the simultaneous operation and endless power supply through tethered systems, commercially available in-line PIG systems operating BEM technology are now available.

# Technology Update

ADVANCED
ENGINEERING
SOLUTIONS LTD

## AESL's ECAT High Flux Magnetic Pipeline Inspection Tools

AESL's magnetic inspection tools are routinely used for the external inspection of grey cast iron, ductile cast iron, wrought iron and steel pipelines, usually for water and gas supply networks.

Since the completion of field trials in Louisville, AESL has undertaken a programme of technology improvements to the mechanical and electronic design of the inspection tool design, and all aspects of the data assessment process and supporting software. The main elements of the improvement programme are summarised below:

### Development of ECAT Inspection Tools

AESL's condition assessment and prediction process requires inspection of the full pipe circumference, using our own magnetic inspection tools. The overall tool profile has now been reduced, to minimise the down hole clearances needed for access and improve the operational usability of the tools.

The mechanical and electronic design has also been updated to give:

- Improvements to the magnetic circuitry to optimise the inspection performance
- Reduced levels of background noise within data signals to improve performance, particularly on grey iron pipe materials
- Increased number of inspection sensors and faster rates of data transfer
- Increased on-board storage for inspection data and additional options for data transfer or downloading

### Development of Calibration and Data Analysis Software

Mechanical and electronic elements of the inspection tool design have been revised to improve the quality and repeatability of inspection performance.

Data analysis software has been further developed to improve the identification and sizing of defects within the inspection data.

Software based calibration procedures have been revised to optimise the overall inspection process.

### Development of Defect Sizing Algorithms

Defect sizing algorithms have been developed, based on the inspection outputs from machined defects within a range of pipe specimens of different material, diameter, wall thickness etc. Parameters investigated to improve the algorithms include

- Influence of defect shape on sensor output and inspection accuracy
- Optimisation of sensor location, orientation, performance
- Benefits of alternative sensor types and configuration.